IMPACIS OF CONGO CONVECTION ON TROPICAL AFRICA'S CIRCULATION, RAINFALL AND RESOURCES.

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ELIARIM ELIMSU MATARI

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IMPACTS OF CONGO CONVECTION ON TROPICAL AFRICA'S CIRCULATION, RAINFALL AND RESOURCES.

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Abstract

The impact of central African convection on surrounding circulation is examined. The convection over the Congo basin is estimated using satellite OLR (Outgoing Long Wave Radiation) as an index. It is then related to the regional and global circulation. OLR indices for the Congo area 15°-30°E, 10°S-5°N are evaluated for JAS and MAM seasons and associated circulation regimes are considered. Seasonal OLR over the Congo for the period 1974-2000 is correlated with selected parameters in the horizontal and vertical plane, in the domain 60°W-90°E, 20°S-15°N. The correlation between rainfall and crop related GDP (Gross Domestic Product) for selected countries which are influenced by Congo convection was evaluated. For cases examined it was found that 20-48% of variance in the GDP growth rate was attributable to local rainfall, clearly showing that human dependence on agricultural activities makes Africa particularly sensitive to shifts in monsoon convection.

Convection over central Africa plays a key role in influencing the weather over the region through latent heating. The influence of Congo convection is short lived compared to that of nearby Indian and Atlantic Ocean monsoons, because of the relative small size and terrestrial nature of the Congo basin. Yet the influence is significant as indicated by the following.

- Zonal winds accelerated from the west from 60 W (Atlantic) through 40 E \$ahel). The relationship extends from surface to 500hPa with a peak at 600hPa.
- Upper westerly winds are weakened over South Africa during JAS season, with the Congo convection leading.
- Congo convection tends to lead the zonal stratospheric QBO, which suggests that the convection is one of the sources of energy for quasi-biennial oscillations in the global climate system.
- Monsoon winds converge over eastern and western coasts of tropical Africa.
- During a wet scenario in JAS season, the Atlantic Walker cell has an ascending arm over the Congo basin, transporting latent heat to the upper atmosphere and higher latitudes, generating standing rossby waves.

TABLE OF CONTENTS.

CHAPTER ONE : INTRODUCTION AND LITERATURE REVIEW

- 1.0 Introduction
- 1.1 Background
- 1.1.1 Climatic background
- 1.2.0 Literature review
- 1.2.1 General Review
- 1.2.2 The interaction between mid latitudes and the tropics
- 1.2.3 Teleconnection of ENSO with Congo rainfall
- 1.2.4 The significance of moisture, wind shear and heating
- 1.2.5 Energy balance over tropical areas
- 1.2.6 Monsoons
- 1.2.7 I.T .C .Z
- 1.2.8 Theory of heat source versas global circulation
- 1.2.9 Why heat release over the western Congo is critical to the global circulation
- 1.3 Motivation and objectives of the study
- 1.3.1 Study objectives

CHAPTER 2: DATA, METHODOLOGY AND INDEX ANALYSIS

- 2.1 Data
- 2.1.1 Introduction
- 2.1.2 NCEP/NCAR Data Project
- 2.1.3 Derived Parameters
- 2.1.3.1 Divergence and Velocity Potential
- 2.1.3.2 Precipitable Water
- 2.1.4 Hovmoller Analysis
- 2.1.5.1 Teleconnection Indices
- 2.1.5.2 ENSO
- 2.1.4.5.3 Quasi-biennial Oscillation Index(QBO)
- 2.2. Methodology
- 2.2.1 Isolation of circulation Regimes:
- 2.2.2 Principal component analysis (PCA).

- 2.3.1 Continuous Wavelet analysis(CWT).
- 2.3.2 Cross wave spectrum
- 2.4.0 Intra-seasonal variability analysis
- 2.4.1 The importance of pentad analysis of convection using OLR.
- 2.4.2 Spectral analysis

CHAPTER THREE: CLIMATOLOGY AND MEAN CIRCULATION PATTERNS

3.0 The climatology and the mean circulation pattern during MAM and JAS

seasons over central Africa.

- 3.1 Introduction:
- 3.2 The climatology of parameters(1958-2000
- 3.2.1 Mean geopotential heights for 850hPa for MAM and JAS season
- 3.2.2 Vertical motion at 500hPa(Omega) for MAM and JAS seasons
- 3.2.3 Mean Precipitable water for MAM and JAS seasons
- 3.2.4 Velocity Potential for MAM and JAS seasons
- 3.3North-South Vertical sections
- 3.3.1 Mean Meridional wind Vertical section for MAM and JAS season
- 3.3.2 Mean Zonal wind vertical section for MAM and JAS seasons
- 3.3.3 East-West section Meridional wind for JAS season.
- 3.4. Hovmoller for selected parameters
- 3.4.0 Introduction
- 3.4.1 Precipitable water
- 3.4.2 Mean air temperature at 700hPa
- 3.4.3 Mean rainfall
- 3.4.4 Comparison of NCEP and CRU rainfall for JAS and MAM seasons

CHAPTER FOUR: TEMPORAL VARIABILITY OF AFRICAN MONSOON INDICES

- 4.0 Introduction
- 4.1 Analysis of Congo convection
- 4.2 Composite analysis for vector winds at 700hPa using Congo index
- 4.3 Congo convection and the zonal wind at 700hPa over West Africa
- 4.4 Composite analysis for JAS-2 to JAS+2 for 200hPa vector winds using Congo

index

- 4.5 Congo convection and the zonal wind at 200hPa over South Africa
- 4.6 Congo convection and NINO3 SST
- 4.7 Congo convection and QBO
- 4.8 Correlation analysis
- 4.8.1 The PC rainfall within the bimodal rainfall area
- 4.8.2 Correlation between tropical bimodal rainfall indices and apriori predictors over selected key areas
- 4.8.3 Correlation between Congo OLR and PC rainfall indices within the region together with known key predictors.
- 4.8.4 Correlation of seasonal OLR over Congo and seasonal JAS rainfall for PC's 1,3,8,12 for the period 1974-2000
- 4.8.5 Correlation of seasonal OLR over Congo and seasonal DJF rainfall for PC's 2,13,10 for the period 1974-2000
- 4.9 Summary:

CHAPTER 5: LAG CORRRELATION PATTERNS WITH RESPECT TO CONGO CONVECTION.

- 5.0 Spatial correlation of Congo convection (inverted OLR) and other parameters.
- 5.1 Introduction
- 5.2.0 Spatial correlation of Congo convection and other parameters at

MAM-2 to MAM+2

- 5.2.1 850hPa for MAM season zonal wind with OLR over Congo.
- 5.2.2 200hPa for MAM season zonal wind with Congo OLR
- 5.2.3 850 hPa and 200hPa Meridional wind for MAM-2 to MAM+2
- 5.2.4 Precipitable water for MAM season with OLR over Congo
- 5.3.0 Spatial correlation of Congo convection and other parameters at JAS-2 to JAS+2
- 5.3.1 Corrrelation of the zonal wind at 600hPa and 200hPa for JAS-2 to JAS+2.
- 5.3.2 Corrrelation of the zonal wind at 200hPa for JAS-2 to JAS+2.
- 5.3.3 850 hPa Meridional wind JAS-2 to JAS+2
- 5.3.4 200 hPa Meridional wind JAS-2 to JAS+2

- 5.3.5 Precipitable water for JAS-2 to JAS+2.
- 5.4.0 Vertical sections N-S and E-W sections for significant cases.
- 5.4.1 Correlation of zonal wind in E-W vertical section at 5N to 5S from 60°W to 70°E with Congo OLR for JAS+2 to JAS-2
- 5.4.2 Zonal wind MAM+2 to MAM-2 N-S Vertical section correlation with Congo OLR at 10W 20W from 35°S to 20°N
- 5.4.3 Zonal wind MAM+2 to MAM-2. E-W Vertical section correlation with Congo OLR at 20S 35S
- 5.5 Summary:

CHAPTER 6: CONGO CONVECTION AS A DRIVER OF THE AFRICAN MONSOON

- 6.0 Introduction
- 6.1 The African Monsoon
- 6.2.0 Relationship between Congo convection and the monsoons.
- 6.2.2 Velocity potential at upper levels for MAM-2 to MAM+2
- 6.2.3 500 hPa Vertical motion (Omega) for JAS-2 to JAS+2.
- 6.2.4 Correlation of Velocity Potential at upper level and Congo OLR for MAM and JAS seasons
- 6.2.5 Correlation of SST and Congo OLR
- 6.2.6 Correlation of Precipitable water and Congo OLR for MAM and JAS seasons

6.3 Summary.

CHAPTER 7: MODEL DEVELOPMENT AND RESOURCE IMPACTS.

7.0 Statistical Modeling of rainfall over African areas using Congo OLR as a predictor.7.1 Model choice

- 7.2 Regression analysis
- 7.3 Use of Congo OLR to predict rainfall over other parts of the region using a regression analysis method.
- 7.4 Model results for Ocean monsoon predictors.

7.4.1 Model results for Zonal wind at 700 hPa as predictor of JAS PC rainfall.

- 7.4.2 Model results for Congo OLR as predictor of DJF PC rainfall.
- 7.4.3 Model for forecasting DJF rainfall over PC10 (West South Africa)

- 7.5 Social economic impact and physical resource levels
- 7.5.0 Impacts of climate on social-economic and physical resource levels
- 7.5.1 Introduction
- 7.5.2 Climate and economic change in rural tropical Africa.
- 7.5.3 A brief analysis of selected cases of impact of climate to the economy.
- 7.5.3.1 Zambia case study
- 7.5.3.2 Tanzania case study:
- 7.6 Summary

CHAPTER 8 SUMMARY AND CONCLUSION

- 8.0 Introduction
- 8.1 Summary of Chapter 3
- 8.2 Summary of Chapter 4
- 8.3 Summary of Chapter 5:
- 8.4 Summary of Chapter 6
- 8.5 Summary of Chapter 7
- 8.6 Conclusion and recommendations

LIST OF FIGURES.

- Figure 1.1 Topographic map of Africa
- Figure 1.2 NDVI maps for Africa
- Figure 1.3 Rainfall maps for April and August
- Figure 2.1 Congo convection and rainfall for JAS and MAM seasons
- Figure 2.2 Analysis of Congo convection
- Figure 2.3 Congo OLR time series for JAS and MAM seasons
- Figure 2.4 Relationship between OLR and rainfall over Congo
- Figure 2.5 Location of the key area using PC analysis
- Figure 2.6 Periodogram for pentad OLR and its modulus spectrum over Congo
- Figure 3.1 Mean MAM and JAS geopotential heights at 850hPa
- Figure 3.2 Mean MAM and JAS Omega at 500hPa.
- Figure 3.3 Mean MAM and JAS precipitable water.
- Figure 3.4 Mean MAM velocity potential lower and upper level.
- Figure 3.5 Mean JAS velocity potential for lower and upper level.
- Figure 3.6 Mean MAM and JAS vertical section of meridional wind at 15°-25°E.
- Figure 3.7 Mean MAM and JAS vertical section of zonal wind at 15-25°E.
- Figure 3.8 E-W Mean meridional and zonal wind for JAS season 0N- 5°N
- Figure 3.9 Hovmoller for seasonal cycle of precipitable water.
- Figure 3.10 Hovmoller for mean air temperature at 700hPa.
- Figure 3.11 Hovmoller for mean rainfall
- Figure 3.12 Comparison of gauge rainfall and satellite estimated rainfall
- Figure 4.1 Analysis of Congo convection
- Figure 4.2 Composite analysis of 700hPa winds JAS season using Congo index
- Figure 4.3 Relationship between Congo convection and zonal winds over West Africa at 700hPa.
- Figure 4.4 Crosswavelet analysis of the relationship between Congo convection and zonal winds over West Africa at 700hPa.
- Figure 4.5 Composite analysis of 200hPa winds JAS season using Congo index
- Figure 4.6 Relationship between Congo convection and zonal winds over South Africa at 200hPa.

- Figure 4.7 Crosswavelet analysis of the relationship between Congo convection and zonal winds over South Africa at 200 hPa for JAS season
- Figure 4.8 Relationship between Congo convection and NINO3
- Figure 4.9 Crosswavelet analysis of the relationship between Congo convection and Nino3
- Figure 4.10 Relationship between Congo convection and QBO
- Figure 4.11 Crosswavelet analysis of the relationship between Congo convection and QBO
- Figure 4.12 Africa PC rainfall analysis.
- Figure 4.13 Location of key areas used as predictors for rainfall over tropical Africa.
- Figure 4.14 Conceptual model showing the impact of Congo convection to the surrounding circulation.
- Figure 5.1 Correlation of Congo OLR and Zonal wind at 850 hPa MAM season.
- Figure 5.2 Correlation of Congo OLR and Zonal wind at 200hPa MAM season.
- Figure 5.3 Correlation of Congo OLR and Meridional wind at 850hPa MAM season.
- Figure 5.4 Correlation of Congo OLR and Meridional wind at 200hPa MAM season.
- Figure 5.5 Correlation of Congo OLR and Precipitable water for MAM season
- Figure 5.6 Correlation of Congo OLR and Zonal wind at 600hPa JAS season.
- Figure 5.7 Correlation of Congo OLR and Zonal wind at 200hPa JAS season.
- Figure 5.8 Correlation of Congo OLR and Meridional wind at 850hPa JAS season.
- Figure 5.9 Correlation of Congo OLR and Meridional wind at 200hPa JAS season.
- Figure 5.10 Correlation of Congo OLR and Precipitable water for JAS season
- Figure 5.11 Correlation of zonal wind and Congo convection for JAS season for E-W vertical section for 5°N-5°S JAS season.
- Figure 5.12 Correlation of zonal wind and Congo convection for MAM season for N-S vertical section at 10°W 20°W.
- Figure 5.13 Correlation of zonal wind and Congo convection for MAM season for E-W vertical section at 20°S-35°S.
- Figure 6.1 Location of tropical easterly jet and African easterly jet and associated weather in a N-S direction.
- Figure 6.2 Definition of African monsoon.

- Figure 6.3 Composite analysis of velocity potential during MAM season.
- Figure 6.4 Composite analysis of vertical velocity during JAS season.
- Figure 6.5 Spatial correlation of Congo OLR and velocity potential at upper levels for MAM and JAS seasons.
- Figure 6.6 Spatial correlation of Congo OLR and SST during MAM and JAS seasons.
- Figure 6.7 Spatial correlation of Congo OLR and precipitable water
- Figure 7.1 Time series for observed and forecast JAS rainfall for PCI (East Sahel) using first 16 years of zonal wind at 700hPa as a predictor.
- Figure 7.2 Time series for observed and forecast JAS rainfall for PCI (East Sahel) using last 16 years of zonal wind at 700hPa as a predictor.
- Figure 7.3 Time series for observed and forecast DJF rainfall for PCI0 (W.South Africa) using first 16 years of Congo OLR and NINO3 SST as a predictors.
- Figure 7.4 Time series for observed and forecast DJF rainfall for PCI0 (W.South Africa) using last 16 years of Congo OLR and NINO3 SST as a predictors.
- Figure 7.5 Contribution to GDP for some Tropical Africa countries.

Figure 7.6 Relationship between maize yield and rainfall in Tanzania.

- Figure 7.7 Conceptual model relating maize yield in Tanzania and east Indian zonal wind
- Figure 7.8 Relationship between maize yield in Tanzania and east Indian zonal wind
- Figure 7.9 Variation of Tanzania GDP growth rate compared to the variation of rainfall.
- Figure 8.1 Idealized cross circulation at the entrance and exit regions of the tropical easterly jet.
- Figure 8.2 Schematic diagram of vertical motion during JAS season.
- Figure 8.3 Correlation pattern of Congo convection and rainfall over equatorial zone.

LIST OF TABLES:

Table 2.1 List of parameters used in the study.

- Table 4.1 Correlation between tropical Africa bimodal monthly rainfall indices and global parameters.
- Table 4.2 Correlation of Congo OLR and regional and global parameters.
- Table 4.3 Correlation of Congo OLR and JAS seasonal rainfall for selected PC's
- Table 4.4 Correlation of Congo OLR and DJF seasonal rainfall for selected PC's
- Table 7.1 Correlation of Congo OLR in combination with other parameters to forecast JAS rainfall over selected PCs.
- Table 7.2 Correlation of Congo OLR in combination with other parameters to forecastDJF rainfall over selected PCs.
- Table 7.3 Population growth and food demand for SADC countries.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.0 Introduction

1.1 Background

The variation of rainfall over tropical Africa can be attributed to atmospheric-ocean interactions and monsoonal processes. It can have profound influences on vegetation, animals and human activities. The Congo basin is the convective "hot spot" in tropical Africa, as deduced from the global analysis of latent heat >120 watts/m². It is only exceeded by the western Pacific Ocean and it is equivalent to the Amazon basin.

Land use activities have contributed to the degradation of the soil in the marginal zones around the Congo to the extent that it can no longer adequately support high productivity. Populations in the marginal areas have increased and prompted an increase in demand for food, and other resources.

The economy of tropical Africa is largely dependent on rain fed agriculture, and is highly vulnerable to the distribution of rainfall. Efforts to achieve food security in most parts of Africa have been hampered by civil wars, political volatility, conditions of international trade, population growth, floods and droughts. Floods and droughts are natural events, which can be anticipated. Both cash and food crops are vulnerable to fluctuations in the amount and distribution of rainfall. Such fluctuations often lead governments to search for alternative food resources. Diseases normally increase during and after the seasonal rains. Adverse effects of droughts or floods can be minimized if we understand the underlying processes. The global climate system is known to consist of highly interactive processes. The El-Nino Southern Oscillation (ENSO) is known as an ocean-atmosphere interaction that drives the inter-annual variability of rainfall over the tropics from Africa to Indonesia to South America via changes of sea surface temperature in the Pacific, and elsewhere, (Nicholson and Entkhabi,1987; Ropelewski and Halpert,1987; Ogallo,1988; Ogallo et.al.1988;

Farmer, 1988; Beltrano and Camberlin, 1993). Hastenrath et.al., (1993) found that East Africa OND rainfall was associated with the Southern Oscillation through zonal pressure gradients produced by SST anomalies in the Indian Ocean. In high phase events, SSTs are cool in the west Indian ocean and surface westerly wind anomalies result in divergence over equatorial East Africa. A global La-Nina thus acts to suppress convection from October to December. Since rainfall anomalies over parts of tropical Africa have been associated with ENSO, the physical basis may be explained in terms of the atmosphere-ocean interaction linked with ENSO. Another phenomena which is active over the Pacific and Indian Ocean is the Intra seasonal wave (Madden and Julian 1971, Lau and Chan 1983). So far the physics of tropical African rainfall has not been exhaustively investigated. The objective of this research is to study the inter-annual variability of seasonal rainfall over tropical Africa and the impacts of heat release from the Congo basin on the regional and global circulation. From this, regional and global ocean atmospheric parameters which influence inter-annual rainfall variability over tropical Africa (6°S-5°N) will be identified. The study will highlight the relationship between inter-annual variability of convection over tropical Africa and ocean- atmosphere coupling. This will be achieved by analyzing available observation and model derived data.

1.1.1 Climatic background.

The focus area lies between 6°S- 5°N, 10°E- 40°E.with elevations from 100 to 700m The areas to the west of 30°E are low lying jungle and include the Congo basin, North Angola, Gabon, Guinea and South Cameroon. **fig. 1.1** The study will consider the Congo basin 15°-30°E 10°S- 5°N, due to the deep convection that occurs there.

The mean state of atmospheric motion is basically due to latitudinal temperature differences, the distribution of continents, oceans and major surface topography. The heating of the equatorial belt through the absorption of incoming solar radiation and the cooling of the polar regions through outgoing terrestrial radiation, provide energy to move the atmosphere and oceans. The mean circulation produces a seasonal cycle in precipitation, temperature and zones of inter-tropical convergence. Over tropical Africa monsoon and trade wind flows and



Fig. 1.1 Relief map of Africa showing rivers. Topographic heights given in the scale.

The study area lies between 5°N to 6°S.

tropical wave motions are present. The major latent heat source area over the Congo basin is of critical importance. In the following sections the climate of the study area is described.

Areas which experience bimodal rainfall in tropical Africa spans from 5°N to 6°S over East Africa and slanting southwards to 10°S westwards into the Congo basin. The region has large spatial and temporal variations of rainfall due to the existence of the complex geographic features and the Congo basin. The Congo basin is affected by the westerly moisture incursions during the northern hemisphere summer when the zonal component of the ITCZ is to the northeast. In the Congo basin the areas to the south of the equator receive their rains during March to May while to the north the rains start from July to October.

The Congo basin is one of the moisture sources for the nearby regions. Moisture from the Congo spreads out depending on the direction of the winds, which is determined by the position of the ITCZ and the surrounding monsoons. The basin receives a moisture influx from the tropical Atlantic and it produces its own through evapotranspiration as shown by the NDVI Satellite vegetation map for MAM season and JAS season. **figure 1.2**. The NDVI for Congo does not change very much from one month to another because of the abundance of moisture throughout the year. The moisture influx depends on the circulation of the Atlantic and the disposition of the monsoon in the Indian Ocean.

1.2.0 Literature review

1.2.1 General Review

The inter-annual rainfall variability and fluctuations that are associated with atmospheric circulation changes in tropical Africa are modulated by the Southern Oscillation, (Ogallo, 1988; Nyenzi, 1988). It is also true for southern Africa, (Tyson 1986(a); Schuleze, 1986; Lindesay et al 1986; Lindesay and Harisson et al 1986; Van Heerden et al., 1988; Ropelewski and Harpert, 1989; and Jury 1992). A number of studies have identified spectral energy in East Africa rainfall consistent with global phenomenon such as ENSO and QBO (Troup, 1965; Trenbeth, 1976; Wright, 1985). In all the studies very little has been done for



Fig. 1.2 Mean NDVI images for MAM season(upper panel) and JAS season(lower panel). Green areas show vegetation and brown ones show little or no vegetation.

the Congo basin due to lack of surface observations but it can be assumed that the teleconnections for the eastern part of the Congo basin are similar to those of East Africa.

Goddard and Graham (1999) studied the relative contributions of the Indian and Pacific ocean sea surface temperatures (SSTs) to rainfall variability over eastern and southern Africa during the austral spring and summer. They contended that the variability of African rainfall is related to the two oceans and even the variability in the two oceans is related. The Pacific and the Indian oceans influence the Walker circulation over the African region and SSTs in the former lead the latter by nearly 3 months.

Casey (1997) examined the southern hemisphere teleconnection patterns and the East African rain season using 500hPa geopotential height and found a pattern of anomalies, that propagate in higher southern latitudes in the form of baroclinic transient waves. These transients increase the zonal flow by their contributions to the meridional thermal gradient. This change in activity is related to the phase of the ENSO cycle.

Recently Kiladis (1997) studied large-scale circulation anomalies of the southern hemisphere during extreme ENSO events. Hastenrath, et al (1993) examined the atmosphere-ocean mechanisms of rainfall anomalies of East Africa. It was observed that during warm events strong convection over the central Pacific drives a divergent circulation. A baroclinic structure in pressure anomalies exists in association with diabatic heating over southern Africa. Large-scale convection during ENSO events is the main forcing mechanism, which modifies the African circulation. It was suggested that the observed global teleconnection associated with ENSO events can be explained by the Rossby wave propagation mechanism.

Several methods have been used to study intra-seasonal oscillations. Common methods are spectral and cross-spectral analysis, Emperical orthogonal functions (EOF), composite and hovmoller analysis on daily or 5 day pentad data. Modeling has also been used in studying intra-seasonal oscillations.

Madden and Julian(1971) noticed a coherence between surface pressure, zonal winds, and temperature at various levels over a period from 41 to 51 days. The oscillation was the result of an eastward movement of large scale circulation cells oriented in the equatorial (zonal) plane. Observational studies by Knutson and Weikmann (1987) and Rui and Wang (1990) have shown that the MJO is characterized by eastward propagating planetary scale convective and circulation anomalies. It is easily observed in the upper level 200hPa zonal winds and is strongest over the warm pool and is absent over cooler waters. The fundamental question from the above studies is how can our understanding be applied to look at how the Congo convection affects nearby regions due to its huge source of latent heating estimated to be of the order of 10^{14} watts.

Several models have been used to study the response of the atmosphere near the equator. Matsumo (1966) applied a quasi-geostrophic model to the tropics and revealed the important waves. In his analysis he considered a homogeneous barotropic fluid, no meridional motion and beta plane approximation. The normal mode solution of the linearized shallow water equation was westward moving Rossby waves, eastward Kelvin waves and gravity waves. It was found that in gravity waves there is considerable cross-isobaric flow at the equator, in Rossby waves, the flow at the equator is mainly zonal and in quasi-geostrophic balance. Equatorial waves (Kelvin) with maximum amplitudes near the geographical equator are important. The amplitudes of such waves (Kelvin) decrease away from the equator. These waves are important for the slowly drifting Walker circulation in the zonal plane, 30-50 day oscillation in the troposphere and even for the ENSO. The waves transmit some teleconnection patterns, which may be identified through PCA analysis. The Rossby waves help explain the interactions between tropical and mid latitude weather systems.

Other studies have been documented by Gill (1980); Webster (1972, 1973) and the following characteristics of the tropical atmosphere have been identified.

- (a) In the zonal plane (x, p), equatorial Kelvin waves move eastwards relative to the mean flow, with upward motion over the heat source.
- (b) Due to coriolis force, increasing away from the equator, planetary Rossby waves appear

Lau and Lim(1984) used a linear model to study the propagation of waves from the tropics to mid latitudes due to tropical convection under westerlies and easterlies. In the westerly wind regime, barotropic Rossby waves propagate to the extratropics and this implies that an extratropical teleconnection will be generated in equatorial westerlies. Simple numerical models have been utilized to study the influence of tropical thermal forcing on the tropics and extra tropics (Hoskins and Karoly, 1981, Webster 1981). Results of the simulations indicated that stationary Rossby waves with low wave numbers can be transmitted from low latitudes via thermal forcing to high latitudes. High wave numbers were confined to the tropics. A barotropic structure in geopotential and temperature appeared outside the tropics. It was concluded that the response of the atmosphere to tropical thermal forcing takes the form of Rossby wave-trains of alternating high and low pressure that are seen along great circle route across the sphere in the upper levels. Most of the barotropic studies indicate that the heating of the upper levels of the equatorial troposphere by the release of latent heat is the driving mechanism of the Rossby wave propagation, in the axis of the subtropical jets.

1.2.3 Teleconnection of ENSO with Congo rainfall

It is well known that ENSO plays a key role in generating interannual variability in all three oceans, which in turn have a major impact on the rainfall over the tropical region. Anomalies of the sea surface temperature in the tropical Pacific force changes in the atmospheric circulation. Anomalies are of the same sign in the tropical Indian Ocean and opposite sign in the tropical Atlantic. The role of air-sea interactions in the tropical Indian and Atlantic oceans is mainly that of an amplifier, by which ENSO induced signals are enhanced in the ocean and atmosphere.

1.2.4 The significance of moisture, wind shear and heating

It has been observed that moisture plays a very important role in enhancing tropical instability. The supply of moisture reduces the role of vertical shear in destabilizing waves. It is also observed that without sufficient moisture supply, the atmosphere is stable and Rossby waves decay faster than Kelvin waves. Kelvin waves are selected near the equator

due to latent heating which is proportional to moisture convergence. The role of the basic state is important in modulating the ITCZ and controlling the teleconnection. In easterly flow evaporation-wind feedback makes the ITCZ propagate poleward and in westerly wind the ITCZ moves equatorward and hence the Atlantic westerlies will enhance the Congo convection. The easterly shear destabilizes and traps the Rossby waves 'in situ' and changes the Rossby wave-structure from symmetric to asymmetric with respect to the equator. In westerly wind shear barotropic Rossby waves resulting from tropic forcing can propagate to the extra-tropics. Teleconnections are confined to the tropics under easterly wind shear. In easterly vertical shear the unstable waves are restricted to the lower troposphere and in westerly vertical shear the unstable waves are confined to the upper troposphere. The preferred unstable wavelength increases with increasing vertical shear and decreases with increasing latent heating intensity. The tilting of the phase lines is useful for determining the stability of the waves. In an unstable Rossby wave, the phase increases with latitude and thus allows the transfer of energy from mean flow to eddies. Heating over land and cooling over the ocean decreases the stability. Therefore with the abundant moisture and latent heat over the Congo basin, the area acts as a source of energy for most of the waves which pass through.

1.2.5 Energy balance over tropical areas

At the earth's surface there is excess energy and as a result a mechanism is required to transport the surplus energy into the atmosphere where a deficit exists. The process of convection, which transports sensible and latent heat away from the earth surface, at 24% and 5% respectively, achieves this. The balance of the net radiation surplus at the earth's surface and the upward fluxes of sensible and latent heat are referred to as the energy balance. Over bimodal areas, which are fairly close to the equator there is an excess energy which must be exported. The form of transport depends on the nature of the surface. On global scales about half of the energy is carried in the form of sensible heat by the advection of warm air masses to colder areas by the general circulation of the atmosphere. Warm ocean currents, taking warm tropical water to high latitudes carry 35%, whilst 15%, is in the form

to propagate westward relative to the mean flow, and generally transfer energy to the west depending on wavelength.

(c) Cross equatorial flow occurs northwards into the region of the heat source. The Rossby waves and Kelvin waves can be used to explain the MJO and some observed tropical synoptic disturbances. MJO can be explained by the Kelvin waves and maintained by the cumulus heating or by the interaction between stationary oscillations and the basic state. Chang (1977) suggested that the MJO is a manifestation of convectively driven equatorially trapped Kelvin waves resulting from interaction between equatorial dynamics and tropical convection.

Wang (1988) carried out an instability study of moist Kelvin waves and showed that the instability of the wave depended on the vertical distribution of moist static energy of the basic state. The induced interior wave and the boundary layer friction supplied the moist static energy to amplify or maintain the unstable waves against energy loses due to long wave radiation and turbulent dissipation.

Eliot (1895) noticed quasi-periodic pressure oscillations in the Indian monsoon tropical region by analyzing surface observations. He suggested that these waves of condensation transmitted slowly in the atmosphere.

Frolow(1941) detected simultaneously pressure oscillations over the whole tropical area from central Africa to central America with period 5-6 days. These oscillations appeared to develop simultaneously over the whole area without any progression in the horizontal.

1.2.2 The interaction between mid latitudes and the tropics.

The question to be asked is, how does the impact of a quasi-stationary heat source influence the surrounding circulation. The influence of mid latitude surges has been demonstrated by Lim and Chang(1983) who used the shallow water equations with the time dependent forcing. For slow forcing the atmosphere response was to generate Rossby and Kelvin waves while for fast forcing, mixed Rossby gravity waves and inertial gravity waves were obtained. of latent heat carried by winds. The movement of this energy helps in maintaining the global energy balance and also explains the global temperature patterns.

1.2.6 Monsoons

The problem of defining and identifying monsoon regions has been considered by many scientists (Ramage 1971, Murakami, Wang & Lyons, 1992). According to Ramage (1971), these areas experience a reversal of surface winds, mainly in the meridional plane.

During the southern summer the winds over Africa are north-easterly becoming northwesterly as we move south of 10°S. During northern summer the winds are south-easterly becoming south-westerly as we move north of the equator. The monsoons are such a dominant feature that the social and economic welfare of many tropical countries is intimately linked to the vagaries of the annual monsoon cycle.

The monsoon winds have a major influence on the rainfall pattern over tropical Africa. The behaviour of the winds is controlled by the following factors.

- (a) The intensity of the continental trough
- (b) Strength and position of oceanic highs
- (c) Cross equatorial flow.
- (d) Upper level anticylones and easterly flow
- (e) Cloud cover and rainfall
- (f) Moist static stability of the lower troposphere

1.2.7 I.T.C.Z.

In tropical latitudes in the lower troposphere there is a surface discontinuity with horizontal velocity convergence and upward vertical motion on the global scale. There is cloudiness near this surface, aligned in nearly east-west direction. It oscillates north-south in response to the position of the sun. The wind discontinuity is between the westerlies in the near equatorial region and easterly trades on the other side of it.

Characteristics of the ITCZ:

(i) It is the equator-ward limit of the Hadley cell. It is near the upward limb of this cell.

- (ii) In area to the west of 10°E extending into the Atlantic Ocean, the ITCZ lies to the north of equator throughout the year.
- (iii) To the east over Africa the ITCZ is to the north during northern summer and to the south during the southern summer. In its annual oscillation, the ITCZ migrates furthest away from the equator into the summer continental regions.
- (iv) On the surface, ITCZ seeks regions of highest temperatures and wind confluence for its location. Over the oceans, the surface position of ITCZ nearly coincides with the region of highest SST.

The ITCZ avoids the geometrical equator. It maintains a seasonal position a few degrees to the north and south of the equator. When the trades on either side of the hemisphere cross the equator they experience a change of direction developing a westerly component due to the coriolis force. There is a cyclonic wind shear across the ITCZ with a westerly wind component on the equatorial side and an easterly component on the poleward side of the ITCZ. On the planetary scale the ITCZ is regarded as a zone of convergence in the lower levels and hence the zone of upward motion. However there are synoptic scale and mesoscale systems, which simultaneously operate in this zone with their own individual vertical circulation's and zones of horizontal velocity convergence and divergence.

In general there is tropical moist air on either side of the ITCZ. On the poleward side subsidence occurs from the descending limb of the Hadley cell and the air is relatively warm dry and stable. Hence the air on the equator side is cooler than the pole-ward side of the ITCZ. Being a region of low pressure the ITCZ slope upwards towards the cooler air, consistent with the hydrostatic approximation. The vertical slope of the ITCZ is approximately given by:

$$\tan \alpha = \frac{f\overline{T_{\nu}}}{g} \frac{|\Delta u|}{|\Delta T_{\nu}|}$$
 for straight flows and $\tan \alpha = \left(f + \frac{2\overline{u}}{r}\right) \frac{T_{\nu}}{g} \frac{|\Delta u|}{|\Delta T_{\nu}|}$ for curved flows.

Where Δu is the difference in geostrophic wind parallel to the discontinuity of the two sides. ΔT_v is the difference in virtual temperatures on the two sides. The slope is highly variable in space and time on individual days and individual locations and the slope varies from 1:20 to 1:500. The general position of the ITCZ is shown using the mean rainfall pattern for April and August in **figure 1.3**. The slope of the ITCZ is important to the dynamics because the depth of the mixing layer of the ITCZ increases as we move towards the equator and due to potential instability of the equatorial airmass, it becomes easy to generate convective activity. Clouds form in the moist layer on the equator side of the ITCZ with a possibility of forming thunderstorms reaching 15Km. Maximum cloudiness is on the equatorward side of the ITCZ at a distance of about 200-500 km. If the underlying moist layer is shallow there may be little rainfall associated with the ITCZ.

The ITCZ is not a static zone having steady state conditions of cloud. There are oscillations in the distribution and intensity of vertical motion. There are high frequency oscillations and clustering of convection by waves and topographic feautures.

The air from the two subtropical regions meets at the ITCZ. The position of the confluence and the intensity convergence depend on the relative strength of the subtropical anticyclones. The latitudinal position of the ITCZ according to Holton et al (1971) is along a path taken by easterly wave disturbances that require both high θ_e and some coriolis force. The driving mechanism of these disturbances is in the latent heat released through cumulus convection. At this scale and intensity of cumulus convection there is a need of low level frictional convergence(Ekman pumping) and convective instability.

There is a narrow band of convection and heavy precipitation in the region of the ITCZ. Within this narrow region, precipitation exceeds evaporation by about a factor of two. The balance of water vapour in the atmosphere near the ITCZ is maintained through meridional convergence of moisture flux in the lower troposphere. The propagation of the ITCZ over Africa is controlled by the meridional variation of the planetary net radiation and the strong north-south land contrast. Webster (1993) emphasized the importance of the meridional gradient of moist static energy which implied that periodicity's of the convective activities are governed by surface hydrology feed backs. The magnitude of the meridional gradient of SST also influences the migration of the ITCZ. Srinivansansan and Smith (1996) suggested that wind evaporation feedback might explain the meridional migration of the ITCZ. In their



Fig. 1.3 Rainfall map for April(upper panel) and August(lower panel) in mm/day. Shaded areas indicate the average position of the ITCZ.

analysis they showed that mixed Rossby-Gravity Waves (MRG) amplify in the presence of mean easterly winds if there is sufficient moisture in the lower troposphere. Convergence regions due to MRG were found to move poleward in the easterlies, but equator-wards in the presence of mean westerlies. When the Mixed Rosby Gravity waves pass through the Congo basin they amplify because of the abundance of moist air and the prescence of easterlies at upper levels. The moisture is thus propagated by the waves to other parts of the region. This is how the Congo convection transmits its influence to the surrounding circulation, which is the topic of this thesis.

The role of ITCZ in heat transfer

According to Falkovich (1982) about one half of the solar energy received by the earth falls on the tropics where there is a surplus that is accumulated mainly in the oceans. About one third of the energy accumulated in the oceans is carried to middle latitudes by oceanic currents. The oceans transfer the remaining two thirds to the atmosphere mainly by evaporation. When the ITCZ is relatively free from convection, moisture is transported to the subtropical regions in the lower troposphere. When the ITCZ is active with considerable convection, the latent heat of condensation released in the upper levels of the troposphere become manifest as sensible heat and is transported to subtropical latitudes via the upper troposphere.

According to Asnani (1993) the ITCZ is warm cored in the lower troposphere as well as the upper troposphere, while it is cold cored in the middle troposphere. The trade inversion is well defined at the points far from the ITCZ axis. As the axis is approached the inversion tends to rise and also weaken. Below the trade inversion moisture increases. As the ITCZ axis is approached moisture content is maximum at about 800hPa.

In regards to energetics of the system, the kinetic energy released through the ascending motion of relatively warm air in the lower and upper tropospheric layers more than compensates the kinetic energy consumed through the ascending motion of the cool air in the middle troposphere, producing a net surplus of kinetic energy. Available potential energy

in the form of horizontal temperature differentials is generated by cumulus convective heating in the upper troposphere and by an eddy flux of sensible heat from the underlying warm sea surface into the lower troposphere. Available potential energy in the middle troposphere decreases through horizontal diffusion processes. The relatively warm SST adequate to maintain the flow of sensible heat from the sea into the lower troposphere, is regarded as essential for the surface location of the ITCZ. Over the land masses the flow of sensible heat is maintained by condensation released from the convective activity particularly from the Congo basin.

1.2.8 Theory of heat source versas global circulation.

In order to understand the context of Congo convection, we need to relate heating and circulation response. The continuity of sensible heat plus geopotential energy in the atmosphere is largely controlled by the meriodional distribution of precipitational heating, net radiative cooling of the atmospheric column and sensible heat flux from the surface. The poleward transport of momentum by the mean meridional circulation is pronounced in the realm of the winter time Hadley cell, but the annual mean pattern of the total transport of sensible heat plus geopotential energy is dominated by the transient eddy transport of sensible heat, which has a maximum in the zone of the travelling disturbances in mid latitudes.

The transport of water vapour and latent heat in the atmosphere is directly related to the meridional pattern of precipitation and evaporation. The mean meridional circulation affects the equatorward transport of water vapour and latent heat in the tropics, while transient weather eddies account for most of the poleward transport in mid latitudes.

According to Bjerknes (1966, 1969) extratropical teleconnections do not result from changes in the Hadley cells. The influence of the tropical SST anomalies upon the Hadley cells result only in regional climatic variations. (Yarnnal, 1985; Yarnal and Kiladis, 1985). Bjerknes argued that the strengthening of the Hadley circulation as a result of tropical SST forcing results in the export of excess heat and angular momentum poleward, reflected by strengthening of the subtropical jet streams and the mid-latitude westerlies (c.f. Harrisson, 1986a). It has since been shown that the extra-tropical response is barotropic while the Hadley cells are baroclinic responses and consequently cannot be involved in extratropical teleconnections (Lim and Chang 1983, Yarnal, 1985 and Kiladis, 1985).

The barotropic response is reflected in the upper tropospheric pertubations generated by the anomalously large latent heat releases associated with positive SST anomalies which in turn produce alternating positive and negative geopotential height anomalies in both eastward and poleward directions from the SST anomaly. It has also been observed that the extratropical response varies seasonally as a result of variability of zonal wind component. In the winter hemisphere the westerlies migrate equatorwards so that there is a greater probability of them overlying the poleward limit of the tropical SST anomaly.

Webster (1982) showed how the seasonal variability in the strength of the zonal winds affects the extent to which the additional latent heat is released in remote areas. Rather than affecting the atmosphere by direct thermal forcing as in the tropics, SST anomalies in mid latitudes are significant in their influence upon cyclogenesis and storm tracks as a result of the strength of SST gradients, which exercise an important control over atmospheric baroclinicity.

SST can also respond to atmospheric anomalies as well as acting as an atmospheric forcing factor. This has resulted into some debate as to the potential for forecasting of SST forcing and the resultant atmospheric circulation anomalies than vice versa (Lough 1986, Chang, 1982, Namias 1982, 1976,1969, Davis 1976). SST responds to atmospheric anomalies as a result of a number of reasons (Perry and Walker 1977). A change in wind velocity can produce anomalous sea water advection, affecting the upwelling process and entrainment. A strengthening of the winds can result in turbulent mixing, hence cooling of the thermally stratified surface layers, which are particularly apparent during the summer months. Anomalous cloud cover can affect the process of heating by insolation. Anomalous ocean atmosphere heat transfers will occur as a result of changes in the air-sea temperature difference and so create instability in the lower levels and assist in the transfer of more water vapour into the atmosphere.

The atmosphere responds to SST anomalies as a result of the transfer of sensible and latent heat and feeds back to the ocean again the transfer of momentum and turbulent mixing of the surface layers. The spatial extent of SST anomalies in low latitudes, the prevalent easterly winds and absence of rotational (coriolis) influences are responsible for the large significance in terms of atmospheric forcing. The magnitude of the tropical SST anomalies is of particular importance because of the non linear relationship between temperature and saturation vapour pressure so that even a small change in SST can result in large changes in latent heat transfers that can also have important thermodynamic implications. Over an area of high SST mid tropospheric heat anomalies occur because of large latent heat energy supply; a mechanism sustaining deep convection.

In the equatorial Atlantic Ocean large scale anomalous sea surface temperatures and ocean circulations have been identified and are shown to be associated with Sahelian rainfall variability (Hisard et al, 1986, Horel et al., 1986; Katz et al 1986; Lamb et al 1986; Philander, 1986; Adedoyin, 1989). Large-scale SST variations in the tropical Atlantic Ocean represent the main component of the variability in the region (Hamilton and Allingham 1988, Lough 1986)

Years of above normal rainfall over the Angola region are associated with positive SST anomalies in most of the east Atlantic Ocean, particularly immediately off the Angola coast (Hirst and Hastenrath 1983a). SST-rainfall coupling in the Angola region is mainly the result of the effect upon the moisture content of the air rather than through an influence upon atmospheric stability (Hirst and Hastenrath, 1983(b), Hastenrath, 1985). The SST anomalies are a response to remote wind stress in the western Atlantic Ocean. A similar positive association between SST in the southeast Atlantic and rainfall over South Africa has been found, although SST anomalies there are more indicative of upwelling rather than an atmospheric forcing mechanism (Nicholson 1986, Walker 1989,1990).

1 - 18

1.2.9 Why heat release over the western Congo is critical to the global circulation.

In the tropical atmosphere, condensation of large amounts of water leads to the release of large amounts of energy, which is the latent heat of condensation. Stability conditions of tropical air masses and the latent heat of condensation are the main driving forces of tropical disturbances.

In order to explain the interaction of heat release from Congo and the global circulation, it will be important to use the equations of motion and thermodynamics as stated by Wang and Li(1993). The simple model is good for describing the fundamental features and required physics. Assuming linear hydrostatic motion for baroclinic mode of the equation of motion can be written as:

$$\frac{\partial}{\partial t} \left(\vec{V} \right) + y \vec{k} \times \vec{V} = -\nabla \phi - \varepsilon \vec{V} \dots \text{eqn. 1.1}$$

$$\frac{\partial \phi}{\partial t} + N\phi + (1 - \delta I) \nabla \vec{V} = -\text{NG}(\text{Ts} - \bar{T} \text{s}) + d(\delta \text{ B- 1}) \nabla \vec{V}_{B} - \delta F |V_{B}| (T_{s} - T_{s}) \dots \text{eqn. 1.2}$$

Where ϕ and \vec{V} represent the non dimensional geopotential and horizontal velocities in the lower free troposphere. The nine non dimensional parameters in the equation are:

$$\varepsilon = \frac{\varepsilon_{\bullet}}{\sqrt{\beta C_o}}, \qquad N = \frac{\mu}{\sqrt{\beta C_o}}, \qquad I = \frac{RL_c b}{C_p P_2 S_2 \Delta_p} \bar{q_e}, \qquad G = \frac{\Delta p}{2p_2} r, \qquad d = \frac{P_s - p_e}{\Delta p}$$

$$\mathbf{F} = \left(\frac{C_o}{\beta}\right)^{0.5} \frac{\rho_s g L_c b}{2C_p p_2} C_E K_q , \qquad \mathbf{A} = \frac{P_s - P_e}{2p_e}, \qquad \mathbf{E} = \frac{\rho_s g K_p}{(p_s - p_e)\sqrt{\beta C_o}}$$

 ε represents the Raleigh friction coefficient,

N is the Newtonian cooling coefficient,

I is the heating coefficient due to free troposphere moisture convergence,

B is the heating coefficient due to boundary layer moisture convergence,

- G is the coefficient of long wave radiational forcing.
- D is the depth of the boundary layer
- F is the coefficient of evaporation forcing
- A is the coefficient of SST gradient forcing
- E is the Ekman number in the boundary layer.

1 - 20

For steady mean circulation motion as $\frac{\partial}{\partial t} \rightarrow 0$ then equation 1 becomes

$$N\phi + (1 - \delta II)\nabla \vec{V} = -NG\left(T_s - \bar{T}_s\right) + d(\delta B - 1)\nabla \vec{V}_B - \delta F \left|\vec{V}_B\right| (T_s - T_*) \dots \text{eqn. 1.3}$$

Where $\phi = \frac{1}{2}(\phi_3 - \phi_1)$ is the thickness between 850 hPa and 500 hPa levels or between 500hPa and 200 hPa levels. It can therefore be observed that ϕ is a function of radiational forcing, moisture convergence heating and evaporational forcing.

The radiational forcing is represented by $-NG\left(T_s - \tilde{T}_s\right)$, a deviation from its domain mean. This means that a larger temperature deviation from the domain mean will be associated with larger geopotential thickness.

The moisture convergence heating is represented by the expression $d(\delta B - 1)\nabla . \vec{V_B}$ which is associated with free tropospheric moisture convergence and boundary layer moisture convergence. The large values of thickness are associated with high moisture content. The contribution due to this term is quite significant over the Congo basin because there is always plenty of moisture due to the convergence of moist westerlies from the Atlantic Ocean, local evapotranspiration from the African jungle and easterlies from the Indian Ocean. These winds converge into the ITCZ which oscillates northward and southward over Africa depending on the position of the sun.

Evaporational forcing is represented by the expression $-\delta F \left| \vec{V_B} \right| (T_s - T_*)$. This implies that the thickness will increase if the difference between T_s and T_* is large and the frictional velocity is large. The SST gradient forcing is greatest over mid latitudes and the Atlantic Ocean. The Indian Ocean has relatively slack gradient implying a weakness of this term. The weak gradient over the Indian ocean will therefore create a west-east gradient from the Atlantic ocean through the Congo basin to East Africa. This is particularly true during MAM season when we have westerlies in the lower levels traversing from the Atlantic Ocean through the Congo basin, where they pick additional moisture and latent heat and transport it to relatively dry areas to the north and eastern parts of Africa.

1.3 Motivation and objectives of the study

Year to year variations of rainfall create problems for farmers, water resource managers and related industries. The situation becomes serious particularly during periods of drought and flood. Many researchers have attempted to forecast the bimodal rains in the months of March to May using SST's over global Oceans with little success and the October to December seasonal rains using Indian Ocean conditions with some success. The seasonal rains in April to August over the north Congo are the most reliable rains for crop production but their prediction is elusive. Rain-fed agriculture requires management by planners and decision makers. Diseases increase during and after the period of rains and therefore an early forecast of the rains will enable economic decisions on health expenditure. Governments can save money by early preparedness for either drought, flood or disease outbreak. Improvement to the management skills will require a thorough understanding of the processes which generates the rains and subsequent rainfall prediction models. In order to predict seasonal climate, there is a need to identify regional patterns of climate variability on inter-annual scale over tropical areas and relate them to regional and global parameters together with the forcing mechanisms. This study will seek to forecast the seasonal rains over tropical Africa using Congo convection as a "predictor".

1.3.1 Study objectives

The fluctuation of seasonal rainfall over tropical Africa is related to the relative strength of subtropical highs, the ITCZ and the associated monsoon inflow. These factors cause the development of the meridional and zonal axes of convection, hence the rains in the Congo basin and surrounding areas. The east-west overturning circulation of the Atlantic is thought to interact with ENSO to modulate convection over the Congo. SST variability over the Atlantic and Indian Oceans controls a portion of the climate of tropical Africa at the inter-annual time scale and affects the local uptake of global climatic signals (Jury 1999).

The study aims at identifying regional ocean atmospheric parameters which influence interannual rainfall variability over tropical Africa with special reference to the impact of latent heating over the Congo to the regional climate and its coupling to the global circulation.

Therefore the main objectives of the research are:

- To study rainfall variability over equatorial Africa and the interaction of heat release from the Congo basin.
- To identify regional atmospheric parameters which are associated with inter-annual rainfall variability over tropical areas (6°S-5°N, 10-40°E) from which we can develop models for predicting seasonal rainfall.
- To identify the role of SSTs and associated oceanic teleconnections in modulating
- interannual rainfall over equatorial Africa.
- To investigate the influence of Congo convection and heat release in relation to the global circulation or indices thereof.
- To combine the results into predictive concepts and models.

Following this chapter which includes a literature review and objectives, the remainder of the thesis is as follows: Chapter two looks into the data sources and methodology. The scarcity of data over the Congo basin and adjacent Indian Ocean is documented. The National Centre for Environmental Prediction (NCEP), the Comprehensive Ocean Atmosphere Data Sets (COADS) and the Climate Research Unit (CRU) archives provide most of the required data because it is gridded, quality checked and enhanced by model and satellite. The methodology for analysis is included in this chapter. The climatology and mean circulation patterns for MAM and JAS are presented in chapter three. The temporal variability of African monsoon indices is discussed in chapter four. This will also include a discussion of wavelet transform (WT) and composite analysis. Lag correlation patterns with respect to Congo convection are discussed in chapter five. The relationship between Congo convection and the African monsoon is presented in chapter six. Chapter seven presents model development and resource impacts. Chapter eight provides a summary for each chapter, conclusion and recommendations.
CHAPTER TWO

DATA AND METHODOLOGY

2.1 Data

2.1.1 Introduction

The data used in this study comes from the following sources: Climate Research Unit (CRU) of the University of Anglia for gridded rainfall data, the National Centres for Environmental Prediction (NCEP) for atmospheric data and the Comprehensive Ocean Atmosphere Data (COADS) for marine based data. Data for this study is filtered to remove higher frequencies and are normalized with respect to their mean and standard deviation from:

$$Z = \left(\bar{x_i - x} \right) / \sigma$$

Where Z is the normalized standardized departure in values, x_i is individual data points,

x is the historical mean and σ is the historical standard deviation. The value of Z provides immediate information about the significance of a particular deviation from the mean (Nyenzi, 1988). Time series are constructed for different parameters to observe their temporal variations and cluster analysis is applied for spatial identification.

For the study of tropical Africa climate variability, monthly data for a 43 year period: 1958-2000 was used. These include observed rainfall data, wind and its components, sea surface temperature SST), vertical motion, precipitable water, OLR (Outgoing Long Wave Radiation). More accurate data for OLR covers the period 1974-2000. This data has been used in analyzing Congo convection because it is satellite based and it is more reliable than the rain gauge data due to the sparse network over the region.

The main objective of this study is to understand the inter-annual variability of rainfall over bimodal areas of tropical Africa with special reference to the impact of Congo convection on the regional and global circulation. Therefore in order to accomplish this the atmospheric circulation patterns of the surrounding areas are considered from the zonal and meridional lower and upper winds, 500hPa vertical motion, 500hPa specific humidity and velocity potential, all extracted from NCEP reanalysis archives.

2.1.2 NCEP/NCAR Data Project

The National Centres for Environmental Prediction (NCEP) and the National Centre for Atmospheric research (NCAR), reanalysis project that began in 1991 has produced daily atmospheric and surface fields considered to be an optimal estimate of the evolving state of the atmosphere, (Kalnay et al., 1996). It has been argued that some fields such as upper air mass velocity and temperature fields are generally well defined by satellites, ships and land based observations. Different countries have contributed observational data not available in real time. Given the statistical interpolation, representation of physics and first guess assimilation techniques, numerical models provide an estimate of the state of the atmosphere better than would be obtained using observations alone.

The project was initiated to produce global analysis of atmospheric fields in support of needs of the atmospheric research and climate monitoring communities. The project uses a state of the art global data assimilation system and a data base as complete as possible.

2.1.3 Derived Parameters

The reason for analyzing secondary derived parameters, is that such values when used in combination with primary parameters yield results which describe meteorological kinematics and thermodynamic structure (Parker, 1994)

2.1.3.1 Divergence and Velocity Potential

The physical properties of the horizontal two dimensional wind fields (V), can be described by considering the rotational and irrotational terms, also known as non divergent and divergent respectively.

That is $V = V\psi + V\chi$Eqn. 2.1

Where ψ is the stream function (rotational) part of the wind, while χ is the velocity potential (irrotational). In this thesis only the irrotational part of the wind will be analyzed as in Levey (1993).

Divergence as defined by (Bleustein1992) is

 $\partial u / \partial x + \partial v / \partial y = \delta = \nabla_h V$ Eqn. 2.2 u= zonal wind component v= meridional wind component x = longitudinal distance. y= latitudinal distance

The subscript $\binom{h}{h}$ means that the derivatives are computed on a horizontal surface. Horizontal divergence is the fractional rate of change of the area of an air parcel and also defined as the acceleration or diffluence experienced by the air in the local horizontal plane.

2.1.3.2 Precipitable Water

Precipitable water (PW) is a measure of the atmospheric vertically integrated water content. Theoretically it is the depth of water that would be obtained if all the water in the column were condensed into a lower surface of unit area. In mathematical terms, PW is defined between two specific atmospheric levels as:

 $PW = \frac{1}{g} \int q \, dp....Eqn. 2.3$

where q is the specific humidity between pressure levels.

p1 and p2 are 1000hPa and 300hPa respectively.

$$g=9.8 \text{ m s}^{-2}$$

Measurements are in g kg⁻¹ or in millimeters (mm), for purposes of this study PW is in mm and intergration is between the surface (1000 hPa) and 300 hPa. Over the highlands of Africa the integration starts at the 850hPa level.

2.1.4 Hovmoller Analysis

Longitude time (Hovmoller) plots are useful in identifying zonal moving meteorological systems. Anomalies of some meteorological parameters, from which we can infer convection, are used in the analysis in order to identify propagation of intra-seasonal convection oscillation anomalies.

2.1.5.1 Teleconnection Indices

2.1.5.2 ENSO

El-Nino is an extensive warming of the upper ocean in the tropical eastern Pacific lasting up to three seasons linked with a change in atmospheric pressure known as the Southern Oscillation(SO), (Glantz, et al, 1991). The Southern Oscillation is characterized by a seesaw in atmospheric pressure between the western and eastern regions of the Pacific Ocean. Another measure of the magnitude of El-Nino events is the sea surface temperature averaged over the Nino 3 region, which extends from 150W to 90W and 5N to 5S. The return period of El-Nino events is varied, ranging from two to seven years. The intensity and duration of the events are also varied yet predictable to a degree. ENSO events are those in which both El-Nino and Southern Oscillation occur together. El-Nino often begins early in the year and peaks between the following November and January. ENSO events are known to influence rainfall over the African continent (Ropelewski and Halpert, 1987; Ogallo, 1994). The Nino3 SST index in the period 1949 to 2000 is used in this study. The Atlantic and Indian Oceans often mirror ENSO events with a zonal see saw, tilting west(deep)-east(shallow) in warm phase.

2.1.5.3 Quasi-biennial Oscillation Index(QBO)

The Quasi-biennial oscillation is a zonal stratospheric wind reversal over the tropics with an oscillation period of 24-26 months. In this study use is made of the zonal wind index (m/s) at 30 hPa of Marquart and Naujokat, (1997). QBO index data from January 1955-December 1995 is used in this study to match with other data sets.

2.2. Methodology

2.2.1 Isolation of circulation Regimes:

The rainfall pattern over the study area is mainly March –September as seen in figure 2.1. The upper panel shows the annual variation of convection over Congo area 15-30°E, 10°S- 5°N, the middle panel shows the rainfall for MAM season with the maximum rainfall greater than 8mm/day south of the equator. Similar rainfall is north of equator





Fig. 2.1 Unfiltered Congo convection(Negative OLR) top panel, for the area 15-30E, 5S-10N and rainfall (mm/day) pattern for MAM (middle panel) and JAS(bottom) season.

during JAS season as seen in the bottom panel. Analysis of Congo convection shows the pattern for the filtered 1.5-16 years, annual cycles and the modulus spectrum as seen in figure 2.2. The modulus spectrum shows that the Congo convection has cycles with periods of 2-3 years and 2.5-7 years, which are associated with QBO and ENSO respectively.

Composite analysis enables one to simplify the study of climate by averaging extreme events with similar impacts but different causal properties. Instead of using rainfall to select composite cases OLR (Outgoing Long wave Radiation) is used. OLR measures the amount of (cloud forced) radiation reaching the satellite, in Wm². Emitted OLR from cold clouds will be lower whereas OLR from hot surfaces will be higher. This implies that the lower the OLR the higher the convection hence the higher the rainfall amount. From this analysis as seen in figures 2.3(upper panel) and 2.3(lower panel), the selected years for compositing were,

Wet MAM season- 1978,1980, 1993, 1999, 2000

Dry MAM season- 1974, 1975, 1979, 1983, 1998.

Wet JAS season- 1978, 1988, 1994, 1999, 2000.

Dry JAS season- 1974, 1979, 1983, 1996, 1998.

A relationship between seasonal OLR over the Congo basin and gauge rainfall for the period 1974-2000 was worked and a significant correlation of -0.39 for MAM season, - .0.42 for JAS season for a period of 26 years. See the scatter plot in figure 2.4.

A number of studies have found an influence of the Ocean through the Congo basin on the surrounding areas. (Nyenzi 1984, Mpeta 1997, Jury, 1998, Mpeta 2001, Matitu 2001). Little has been done on the influence of Congo convection itself on the surrounding circulation. Based on earlier principal component work by Mpeta (2001) in zoning African rainfall according to season as in figure 2.5. The key area is 5°N-10°S 15°E-30°E as in figure 2.5.



 F_{12} Congo correction. From top left in a clockwise manner filtered 1.5-16 years, inual collection of key area and modulus spectrum of Congo convection.



Fig. 2.3 Time series of mean OLR anomaly MAM season (upper panel), JAS(middle panel) and location of where the data was extracted(bottom panel)



Fig.2.4 Seasonal station gauge rainfall vs OLR over Congo 10°S-5°N, 15-



Fig.2.5 Location of the key area and the dermarcation of bimodal region(PC2) using PCA analysis(After E.Mpeta, 2001)

PARAMETER	LEVEL USED	UNITS
Zonal wind	850hPa and 200hPa	ms ⁻¹
Meridional wind	850hPa and 200hPa	ms ⁻¹
Precipitable water	Integrated from 1000 to 300 hPa	mm
Specific humidity	500 hPa and 700hPa	g/kg
Velocity Potential	850hPa and 200hPa	$m^{-2}s^{-1}$
Geopotential Heights	850hPa and 200hPa	m
Vertical motion(Omega)	500hPa	Pa/s ⁻¹
Divergence	850hPa	S ⁻¹
Sea Surface Temperature	Surface	°C
Water vapour flux	Integrated from 1000 to 500hPa	g/kg s ⁻¹
Rainfall	Surface	mm

Table 2.1 Parameters used in the study

2.2.2 Principal component analysis (PCA).

Principal Component Analysis(PCA) is a multivariate statistical technique having wide applications in meteorology (Lyons, 1982; Yin, 1984; Basalirwa et al., 1998). The method reduces the number of dimensions whilst explaining variability within the original record (Jolliffe, 1993). PCA is done when the original data contains grid point variables that are spatially correlated. It reduces the original data to sub-sets ranked in order of importance.

Principal components (PCs) or modes are produced, each consisting of an eigenvalue that quantifies the variance, a set of loadings (eigenvectors) that describe the spatial distribution (coherent patterns) and a set of time scores that define the evolution. The first PC is a linear function accounting for the highest variance i.e the dominant pattern. The second PC is the linear function with the next highest variance subject to being uncorrelated with the first PC. In this study the PCA analyzed by Mpeta (2002) were used.

2.3.1 Continuous Wavelet analysis(CWT)

In studying the spectral characteristics of geophysical data which may be non -stationary many researchers use standard Fourier Techniques that may yield spectral coefficients that are averaged over the entire measurement period (Meyers and O'Brien 1994). Fourier methods do not produce information on the time evolution of a signal. Wavelet transform (WT) is an analysis tool that is appropriate to the study of multi- scale, non stationary processes occurring over finite spatial and temporal domains (Lau and Wang 1995). This analysis tool is becoming popular for analyzing localized variations of spectral power within a time series. WT resolves a time series within frequency space (Torrence and Campo 1998). Wavelet transform as introduced by Morlet (1983) has found wide application in sciences such as, image processing, optics, turbulence, etc. A number of geophysical studies have used this technique and produced interesting results. Wavelet analyses are growing in use in atmospheric and oceanographic literature (Kumar and Foufola and Georgiou, 1993; Gamage and Blumen, 1993; Weng and Lau, 1994; Meyer and O'Brien, 1994; Gu and Philander, 1995; Wang and Wang, 1996; Baliunas et al., 1997 and Kukakirin, 2000). The time frequency space provide a better picture in understanding the frequency and amplitude modulation within the period of measurement for a number of parameters. A brief introduction to the idea of wavelet transform is presented below; a complete description of geophysical applications can be found in Foufooula-Georgiou and Kumar (1995), while a theoretical treatment of WT is covered in Daubechies (1992) Wavelet Transform Technique.

The WT is a mathematical tool which allows the decomposition of a signal x(t) in terms of elementary contributions called wavelets. These wavelets are obtained from a single function φ by translation s and dilations:

$$\varphi_{b,a}(t) = \frac{1}{a}\varphi\left(\frac{t-b}{a}\right)$$
....eqn. 2.4

where a (>0) is the dilation(scale) parameter and b is the translation (position) parameter, both are real variables. As the CWT will be used to filter the data, here the normalisation 1/a is chosen instead of the usual $1/\sqrt{a}$ (Delprat et al., 1992). The CWT of

the signal x(t) with the analyzing wavelet φ is the convolution of x(t) with a set of dilated and translated wavelets:

$$W_x(b,a) = \frac{1}{a} \int_{-\infty}^{\infty} x(t) \varphi^{\bullet}\left(\frac{t-b}{a}\right) dt \dots \text{eqn. 2.5}$$

where * denotes the complex conjugate. The wave is transformed and defined as continuous (Meyers and O'Brien 1994). The CWT expands the time series x(t) into two-dimensional parameter space (a,b) and yields a measure of relative amplitude of local spectral activity. The scale parameter a in $W_x(b,a)$ corresponds to wavelength or period if the data is spatial or temporal respectively. The choice of the wavelet φ depends on the signal to be analyzed. In this study a wavelet that is well localized in the frequency space is selected. This wavelet is difined by:

$$\varphi(t) = \pi^{-1/4} e^{-t^2/2} e^{i\omega_{0t}}$$
.....eqn. 2.6

where $i = \sqrt{-1}$ and $\omega_{0=5.4}$ is chosen large enough to ensure that φ satisfies the admissability condition:

$$\int_{-\infty}^{\infty} \varphi(t) dt = 0 \dots \text{eqn. } 2.7$$

For the Morlet wavelet, it makes sense to identify the inverse of the scale to a frequency. The relation between the scale a and the usual frequency f is given by (Meyers., 1993)

$$f = \frac{\omega}{2\pi} \left(\frac{\omega_0}{a} + \frac{\sqrt{2 + \omega_0^2}}{\omega_0} \right) \dots \text{eqn. 2.8}$$

The Morlet wavelet can in-fact be interpreted as a band pass linear filter of weight 1/a centered around $\omega = \omega_0/a$. Finally, the CWT with the Morlet wavelet is a time frequency analysis where the dilation parameter corresponds to the wavelength period and the translation parameter corresponds to position or time. Note also that, as the Morlet wavelet is complex, the wavelet is complex, the wavelet transform coefficient $W_x(b,a)$ is also complex and may be expressed in terms of real and imaginary parts,

modulus and phase. Generally speaking the CWT is infinitely redundant: The 1-D original signal being transformed into 2-D time frequency image Nevertheless, the fundamental information can be extracted from the so called ridges of the CWT. These ridges are made of the points in the time frequency representation for which the frequency of the dilated-translated wavelet coincides with the local frequency of the signal . More precisely, the ridges are where the sets of couples (b,a) for which the relation:

$$\frac{\partial \phi_{b,a}}{\partial b} = \left(\frac{\omega_o}{a}\right) \dots \text{eqn. 2.9}$$

is satisfied and where $\phi_{b,a}$ is the phase of $W_x(b,a)$ and ω_o/a is the frequency of the dilated wavelet

2.3.2 Cross-wave spectrum

The relationship between two time series can be investigated in the time-frequency domain by computing their cross- wavelet spectrum. For two time series x(t) and y(t), with wavelet transforms W_x and Wy, one can define the cross wavelet spectrum as

$$W_{xy}(b,a) = W_x(b,a)W_y^{\bullet}(b,a)$$
eqn. 2.10

where $W_{X(b,a)}$ and $W_Y(b,a)$ are the CWT of x(t) and y(t) respectively and where * denotes the complex conjugate. The complex cross-wavelet coefficient $W_{xy}(b,a)$ may be expressed in terms of real and imaginary parts, modulus phase difference. Let us recall if $x_1 = a_1 e^{i\theta_1}$ is a complex number with a modulus a_1 and a phase θ_1 and if $x_2 = a_2 e^{i\theta_2}$ is a complex number with a modulus a_2 and a phase θ_2 then: $x_1 x_2^{\bullet} = a_1 a_2 e^{i(\theta_1 - \theta_2)}$. Where phase is independent of amplitude. Estimation of the instantaneous time delay between two time series is also possible by integration of the cross wave spectrum. This is useful in determining the stability of association.

2.4.0 Intra-seasonal variability analysis.

Introduction:

The year to year variability of summer climate over the bimodal rainfall area of tropical Africa is mainly expressed as intra-seasonal wet and dry spells with varying characteristics. The tropical atmosphere is convectively unstable. For production of clouds and rainfall vertical motion and moist air are required. Within the tropics vertical motion can be induced by forced ascent of air over high ground, horizontal velocity convergence and unequal heating of land and water mass. Large temporal and spatial variations of convection are normally observed within the tropics. The seasonal and inter-annual variations are of particular interest here. Deep convection within the tropics may be modulated by zonal moving waves. The Congo being within the tropics is expected to experience westerly MJO convective variability and with high moisture content, it acts as source of energy for the waves. The main question here is the interannual variability impacts on the African monsoon.

2.4.1 The importance of analysis of convection using OLR

The OLR data helps in bridging the gap of conventional meteorological data over large remote land and oceanic areas. In the tropics, OLR is largely modulated by cloud top temperature and regions of intense convection in the tropics appear as regions of low OLR, whereas cloud free regions appear as regions of relatively high OLR. These properties of OLR data make them extremely useful in monitoring and understanding tropical climate variability. Studies using OLR include the study on the annual and interannual atmospheric variability in the tropics by Heddinghaus and Krueger(1981), Horel et al (1989) who investigated the annual cycle of the convective activity of the tropical America, Muthuvel and Arkin(1992) examined the interannual and long term climate variations in the tropics using OLR data. Motell and Waere (1987) used OLR to investigate quantitative precipitation over the tropical Atlantic Ocean and over the tropical Atlantic Ocean by Yoo and Carton (1988). Janowaiki and Arkin (1991) developed linear regression model to estimate precipitation over global tropics. Xie and Arkin(1998) investigated the relationship between precipitation and OLR and developed a new technique to estimate monthly precipitation for the entire globe. Prasad and Verma (1985) found OLR data useful in the study of large-scale monsoon circulation and associated cloudiness and rainfall over the Indian regions.

2.4.2 Spectral analysis.

The idea behind spectral analysis of a time series is to explore the existence of cyclical patterns of data. The features of spectral analysis is to decompose a time series with cyclical components into a few linear combinations of sine and cosine functions of different frequencies. It is developed as follows:

For k=1 to q:

$$x_{1} = a_{0} + \sum_{k=1}^{q} \left[a_{k} * \cos(\lambda * t) + b_{k} * \sin(\lambda * t) \right].$$
 Eqn. 2.11

where $\lambda = 2 * \pi * f$ frequency expressed in radians.

f = 1/T where T is the period of oscillation

$$q=\frac{n}{2}-1$$

 a_k and b_k are regression coefficients of cosine and sine parameters respectively and tell the degree to which the respective functions are correlated with the data. Periodogram values were then computed as follows:

$$P_k = (a_k^2 + b_k^2) * \frac{n}{2}$$
.....Eqn. 2.12

where,

 P_k is the periodogram value at frequency f_k and n is the overall length of the series. The periodogram values can be interpreted in terms of variance (sum of squares) of the data at the respective frequency or period. Periodograms are then plotted against the frequencies.







Fig 2.6 Congo pentad OLR analysis. From top panel unfiltered, filtered, spectral analysis and modulus spectrum for the filtered 4-14 pentads OLR (bottom panel) for Congo area 15-30°E, 10°S-5°N for the period 1980-2000.

Here the SPLUS software package was used. The data were tapered at 10% to enhance the spectral estimates. Tapering reduces the influence of estimates calculated in one frequency band upon those in another frequency band.

Spectral analysis was done on filtered pentad OLR data covering the period 1980-2000 for Congo area of study 10S-5N, 15-30E. Filtering was done to remove any other cycles and remaining with only annual cycles, **figure 2.6** top panel for unfiltered and second panel for the filtered time series. Periodogram for the filtered data was plotted as seen in third panel. Modulus spectrum analysis was done using a 4 to 14 pentad filter, in order to capture 20 to 70 days oscillations (MJO) as seen in the fourth panel.

The spectral analysis for Congo show major peaks between 4-7 pentads (20-35 days), which are within the Madden Julian oscillation period. figure 2.6(lower panel).

Summary

Here data used in this study of climate variability over central Africa have been discussed. The impact of Congo convection on the surrounding circulation was is sought through analysis methods including, PCA, WT, Spectral analysis and composite. The climatology of tropical Africa is discussed in the following chapter. The annual cycle of rainfall and sea surface temperature, sea level pressure, zonal and meridional wind components are identified, the composite lag structure for MAM and JAS seasons with above and below normal Congo convection are analyzed.

CHAPTER 3

CLIMATOLOGY AND MEAN CIRCULATION PATTERNS

3.0 The climatology and the mean circulation pattern during MAM and JAS seasons over central Africa.

3.1 Introduction:

In this chapter the NCEP re-analysis, COADS and CRU gridded data sets are explored to establish a climatology for rainfall and other kinematic and thermodynamic fields in the region 60°W- 90°E 15°N-20°S. The mean patterns are based on 43 years (1958-2000) of monthly data. The discussion will mainly focus on the bimodal season (March-May) and the unimodal season July to September for the northern part of Congo (5°N-0, 15-30°E). Among researchers who have described the climatological parameters over Africa are Preston-Whyte and Tyson(1988); Theron and Harrison(1989), Pathack (1993), Rocha(1992); Kabanda (1995), Mulenga (1997), Mpeta (2001). The main characteristics are the mean position of the ITCZ, the monsoon flow over Africa and the subtropical marine high pressure systems. Other parameters to be analyzed here are SST, SLP, OLR, PWA(Precipitable Water), U and V winds over Indian and Atlantic oceans.

3.2 The climatology of parameters (1958-2000)

3.2.1 Mean Geopotential heights for 850hPa for MAM and JAS seasons.

During March to May season there is a ridge of high pressure emanating from the south eastern part of the continent to the east of Madagascar. The ridge represents the Mascarene high extending a ridge to the east African coast. A trough of low pressure occurs in a northeast-southwest orientation covering the Congo basin, (figure 3.1 upper panel) for the 850hPa.

The mean geopotential heights for JAS season has the following main features as seen in figure 3.1 850hPa (lower panel). There is a tight gradient over the coast of East Africa, which reflects the strength of southeast monsoon at this season. The ridge emanates from the high to the south of Madagascar. Over the Congo there is a slackened trough





Fig. 3.1 Mean MAM(upper panel) and JAS(lower panel) seasons Geopotential heights(m) at 850hPa for 1958-2000.

extending to the western parts of Africa. Low values of geopotential heights are reflected over the northwestern part of the Indian Ocean.

3.2.2 Vertical motion at 500hPa(Omega) for MAM and JAS seasons.

The vertical motion at 500hPa for MAM season as seen in figure 3.2 upper panel shows a narrow band of positive values running over eastern parts of the continent extending from Mozambique through Tanzania to Kenya and Somalia. An axis of negative values extends from the Gulf of Guinea, through Congo basin to western parts of East Africa. Another axis of negative values extends from the Indian Ocean north of Madagascar and extending to parts of East Africa. The negative values of omega reflect areas of active weather and the positive ones the reverse.

For JAS season as seen in figure 3.2(lower panel), the axis of (uplift) negative values shifts northwards compared to MAM season. The axis is from West Africa 10°N extending to Congo basin and then bending northeastwards.

Most of East Africa is dominated with positive values. Negative values are also reflected over the Indian Ocean at 60°E. The edge of convection extends from western part of East Africa extending to Ethiopia. This is the period of dry conditions over eastern parts of Africa and wet over central and west Africa. The dry conditions act to trap the Atlantic inflow to the Congo, thereby enhancing convection.

3.2.3 Mean Precipitable water for MAM and JAS seasons

In the case of MAM season, the main features of moisture as seen in figure 3.3(upper panel) are, high values which are greater than 40kg m² which are seen over the Indian Ocean extending to the coastal part of East Africa and also over Congo basin extending to the western coast. A narrow zone of low values covers the central part of East Africa. From 30°E moving eastwards, the precipitable water starts to drop until we approach the Indian Ocean, with a drop of 8 kg m². The pattern is similar to the rainfall pattern in the bimodal region.

For JAS season Figure 3.3(lower panel), the axis of high values of precipitable water has shifted northwards compared to MAM season and the whole of East Africa is covered



Fig. 3.2 Mean MAM (upper panel) and JAS (lower panel) season vertical motion, Omega (Pa/s) 500 hPa for 1958-2000.





Fig. 3.3 Mean MAM(upper panel) and JAS(lower panel) season Precipitable Water (Kg/m²) for 1958-2000.

with low values of up to 20Kg m². The high values are consistent with the general position of the ITCZ at this period which is between 15-20°N. The Guinea coast ocean monsoon is clearly demonstrated by the high precipitable water values in the ocean close to the Guinea coast during MAM season and they shift northwards during JAS season when the ITCZ is far to the north (figure 3.3.)

3.2.4 Velocity Potential for MAM and JAS seasons

During MAM season (figure 3.4 upper panel) for lower level velocity potential the main features are, the tight gradient of negative values over South Atlantic close to the Gulf of Guinea extending to Angola and western Congo basin. The gradient becomes loose and positive as we move eastwards. At the same time we have a zonal band of high values over the Sahel region in the lower levels which implies low level divergence and hence no much convection at this period. At the upper levels (figure 3.4 lower panel) an isolated cell of high values exists over Congo basin. The high values are an indication of divergence at upper levels which implies more convection at this period.

During the JAS season as seen in figure 3.5(upper panel) for lower level velocity potential, a tight gradient exists in the Gulf of Guinea from the South Atlantic. A gradient exists in the northeast direction. At the upper levels (figure 3.5 lower panel) a tight gradient with a southwest northeast orientation persists over the whole region. This is the peak period of the Indian monsoon and hence the pattern suggests that Congo convection for JAS season acts as "slave" to the Indian monsoon.

3.3 North-South Vertical sections

3.3.1 Mean Meridional Vertical section for MAM and JAS season.

During MAM season figure 3.6(upper panel), section at 15°-25°E, it can be observed that southerlies are dominant in the lower levels up to 850mbs. Northerlies are dominant in the upper levels starting from 700mbs with a peak at 200mbs, between 15°N-20°S.

During JAS season (figure 3.6 lower panel) for the sector 15°-25°E, southerlies dominate the lower levels up to 800hPa within the entire range 15°N-20°S and in the middle levels



Fig. 3.4 Mean MAM season Velocity Potential (m²s⁻¹) for lower level(upper panel) and upper level(lower panel) for 1958-2000.



Fig. 3.5 Mean JAS season Velocity Potential (m²s⁻¹) for lower level(upper panel) and upper level(lower panel) for 1958-2000.



Fig. 3.6 Mean meridional wind at 15-25°E for MAM season(top panel) and JAS season(bottom panel) for 1958-2000 for vertical N-S section.

between 700-600hPa we have northerlies from equator to 15°N. This pattern forms a shallow overturning circulation. Northerlies are also found at 150hPa at 15S while southerlies are also present at 15N.

3.3.2 Mean zonal wind at 15-25E for MAM(top panel) and JAS(bottom panel) seasons.

Taking a section between 0-5°N for MAM season (figure 3.7 upper panel) the main features are the strong easterlies at 600 hPa and 150 hPa at around 5°E. The 600 hPa easterlies are associated with African low level jet and the 150 hPa easterlies are associated with the tropical easterly jet. During MAM season there is a symmetrical upper westerly influence whereby, we have strong westerlies at 200hPa at 15° on either side of the equator. In the lower levels we have westerlies from the surface to 900hPa. During JAS season, we have strong easterlies from equator to 15°N at 300hPa-100hPa level, and weak westerlies in the lower levels. Strong westerlies can also be observed at 200 hPa between 10-20°S (figure 3.7 lower panel).

3.3.3 East -West section for Meridional wind and zonal wind at 0-5°N for JAS seasons.

During JAS season, the major feature for the meridional wind, is the strong southerly wind $>10ms^{-1}$ between 40°-50°E (figure 3.8 upper panel). This is associated with the full establishment of the southwest monsoon and the east African low level jet. The strong winds are in the proximity of the jet core. The northward flow acts as a trap to the monsoon west of 35°E. At 200 hPa we have relatively weak northerlies.

In the case of the zonal wind the main feature is the presence of strong easterlies at 150 hPa. These are associated with the tropical easterly jet. In the lower levels we have weak westerlies (figure 3.8 lower panel).



Fig. 3.7 Mean zonal wind at 15-25°E for MAM season(top panel) and JAS season(bottom panel) for 1958-2000 for vertical N-S section.



Fig 3.8 E-W vertical section of Meridional wind(upper panel) and zonal wind(lower panel) for JAS season at 0°N-5°N for 1958-2000

3.4 Hovmoller analysis using monthly long term mean within the zone 0°-50°E, 20°S-15°N

3.4.0 Introduction

Longitude-time(hovmoller) plots are useful in identifying onset and decay of the African monsoon. Anomalies of some meteorological parameters from which we can infer convection are used in the analysis to identify propagation of intra-seasonal oscillations. In this study the area chosen above covers the whole bimodal region and the periphery .The monthly sequence starts from January to December.

3.4.1 Precipitable water

The seasonal variation of precipitable water (figure 3.9) indicates that that the highest precipitable water with values $>40 \text{Kg/m}^2$, have peaks during November and April. These are the periods of the short and long rains in the bimodal region. The high values cover the Gulf of Guinea, Cameroon, western part of Congo. During July there are also some high values over the eastern part of Congo. Between 38°-43°E there is a strip of low values, which covers parts of east Africa. To the east of 45°E, the values are high and it covers part of the Indian Ocean.

3.4.2 Mean air temperature at 700 hPa

There is generally a low variation of temperature with time (figure 3.10). Temperatures greater than 8°C can be observed between June and December and less than 8°C, between July and August. The difference between the coldest and the warmest month is approximately 1°C. This is in agreement with the fact that over most of the tropics the temperature difference between the coolest and the warmest month is less than 4°C and over the equatorial oceans is less than 2°C. The actual march of temperature during the course of the year normally follows the pattern of the insolation curve, with the highest temperature during the period around the overhead position of the sun.

3.4.3 Mean rainfall

The variation of CMAP rainfall from June to July shows that maximum rainfall is in the month of October and April. This reflects the seasonal rains for MAM and OND seasons.



Fig.3.9 Hovmoller for Precipitable water(kg/m²) for seasonal monthly mean (1968-1996) at 5S-5N.



Fig.3.10 Hovmoller for Mean air temperature at 700hPa (°C) for seasonal monthly Mean (1968-1996) at 5S-5N.

Most of the rains are confined in the zone $10-30^{\circ}E$ with peak rainfall >10mm day ¹ during April and October. During May to October the rainfall amounts range between 6-8 mm day ¹ (figure 3.11 upper panel). This is the period when we have maximum rainfall over the Congo basin. January is the driest month. Between 35-45°E there is a relatively dry zone with rainfall amounts <2 mm day ¹. This covers parts of East Africa(figure 3.11). The total standardized rainfall pattern is similar to the above with maximum deviation in April and October(figure 3.11 lower panel).

3.4.4 Comparison of NCEP model rain and CRU rainfall for JAS and MAM seasons.

From figure 3.12 it can be observed that the mean gauge rainfall for JAS season (upper panel) is slightly more than the satellite based NCEP rainfall data (lower panel). The data has been averaged for the period 1974 to 2000. This indicates that, in some cases the satellite based data tends to underestimate the rainfall. An example over the Guinea coast the mean JAS rainfall is 11mm day¹. according to the gauge data while according to the satellite based data (lower panel) the estimate is 8 mm day¹, for the same period.

During MAM season (figure 3.12), there little difference between gauge and satellite estimated rainfall. The amounts reflected are almost the same except that the gauge rainfall shows more areas with significant rainfall. Satellite based data is useful particularly over areas with few rain gauges such as the Congo basin.

Summary

In this chapter, the mean climatology and circulation have been discussed for MAM and JAS seasons for central Africa in order to understand the climate for the period 1958-2000. Vertical sections for specific areas for the zonal and meridional winds were examined over 15-25°E, the central part of the continent. Hovmoller diagrams were plotted to study the seasonal cycle of moisture, etc. Comparison between satellite based rainfall gauge rainfall for MAM and JAS seasons were made. This will enable appropriate usage in further analysis. One feauture seen in these results is the development and decay of a monsoon system over the Congo with rainfall >8 mm day ¹ in JAS season. This chapter lays the background for a study of the impact of the Congo convection on the monsoon circulation around Africa.



Fig.3.11 Hovmoller Mean CMAP rainfall (upper panel) and total standardized CMAP rainfall(lower panel) in mm/day for (1968-1996) at 5°S – 5°N.



Fig.3.12 Comparison of gauge rainfall (upper panel) and NOAA satellite estimated CMAP rainfall (lower panel) for JAS season. Units(mm/day)

CHAPTER 4

TEMPORAL VARIABILITY OF AFRICAN MONSOON INDICES

4.0 Introduction

In this chapter the Congo convection is studied in the time domain. Parameters that are significantly correlated with Congo convection are subjected to wavelet analysis to check for the degree and stability of association. The relationship between bimodal PC rainfall areas to each other and to specific parameters over key areas over the Atlantic, Pacific and Indian Oceans are briefly discussed. Then correlations between Congo OLR and other parameters within and outside the region are analyzed using continuous and seasonal data sets.

4.1 Analysis of Congo convection

Analysis of Congo convection (figure 4.1) shows the annual and inter-annual variability and the spectral character. The modulus spectrum shows that Congo convection has cycles with periods of 2-3 years and 2.5-7 years, which are associated with QBO and ENSO respectively.

4.2 Composite analysis for vector winds at 700hPa using Congo index

Composite analysis of vector winds at 700hPa for JAS-2 to JAS+2 was done using wetdry years over the Congo study area as an index. The selected years were, wet JAS season- 1978, 1988, 1994, 1999, 2000 and dry JAS season- 1974, 1979, 1983, 1996, 1998. JAS lag 0 was selected and is presented in figure 4.2. During JAS season the westerly winds over the Guinea coast are fairly strong and they extend into the continent. At the same time over the Indian Ocean we have strong south easterly winds south of the equator changing to southwesterly direction as we cross the equator and heading towards India. This reflects the typical pattern of the monsoon period over this region. From this analysis we can deduce that the convection over Congo has a pulling action on monsoon winds over the Guinea and the Indian Ocean.


Fig. 4.1 Congo convection. From top left in a clockwise manner filtered 1.5-16 years, annual cycles, location of key area and modulus spectrum of Congo convection.



Fig. 4.2 700 hPa vector winds for JAS season at lag 0 using (wet-dry) years over Congo study area. Units m s⁻¹

4.3 Congo convection and the zonal wind at 700hPa over West Africa(5N-10N, 10W-15E).

The Congo convection anomaly is compared with Atlantic zonal wind at 700hPa, in the period 1974-2000 in figure 4.3. There is an indication that the zonal wind is leading Congo convection. Filtered 1.5-16 years time series of the zonal wind at 700hPa show some significant negative anomalies in 1983-84 which could be associated with dry conditions over Congo during the same period. The modulus spectrum of the zonal wind indicate strong signals between 1980-1998 with periods of 2-4 years associated with QBO and 3-8 years associated with ENSO signal

Figure 4.4 shows the stability of association between Congo convection and the Atlantic zonal wind at 700hPa. From top panel, the zonal wind is leading Congo convection with an exception of a few years which implies that the zonal wind acts as an energy source for the convection. The modulus of the cross spectrum indicates that the Congo convection and the zonal wind are in phase in the range 30-48 months (2.5-4 years)



Fig. 4.3 Zonal wind at 700 hPa over West Africa. From top left in a clockwise manne, time series of Congo convection and zonal wind, annual cycle of zonal wind, location of the area and the modulus spectrum of the filtered 1.5-16 years zonal wind.



Figure 4.4. Zonal wind at 700 hPa over West Africa. From top panel time series of 1.5-16 yr. filtered Congo convection and the zonal wind, cross spectrum modulus and time delay curve between the two series.

between 1976-88, 1993-98; and between 50-60 months between 1995-2000. The time delay between the time series shows that the zonal winds leads Congo convection by 0-16 months except for the period 1979-85 when the Congo convection is leading by 0-3 months.

4.4 Composite analysis for JAS-2 to JAS+2 for 200hPa vector winds using Congo index

Using the wet minus dry composite, the upper circulation is analyzed with respect to the Congo convection. Generally easterlies strengthen throughout the hemisphere. The Indian Ocean easterly and south easterlies have strengthened and extended to South Africa with the wind speed over 6m/s over South Africa (figure 4.5) lag 0 JAS season. A divergence pattern is evident over Congo. The divergence at the upper levels over Congo will



Fig. 4.5. 200 hPa Vector winds JAS season at lag 0 using (wet-dry) years over Congo as an index.

encourage low level confluence and hence more convective activity. Over South Africa the strong easterly winds implies upper level diffluence, which encourages low level confluence. This pattern encourages the formation of cut off lows that are well known for

4.5 Congo convection and the zonal wind at 200hPa over South Africa

The Congo convection anomaly is compared with South Africa zonal wind at 200 hPa, in figure 4.6, for the period 1974-2000.

There is an indication that Congo convection is leading the upper zonal wind. Filtered 1.5-16 years time series of the zonal wind at 200hPa are mostly in phases in 1982-83. The modulus spectrum of the zonal wind indicate a strong signals between 1974-1982,1993-1998 with periods of 2-4 and 4-8 years associated with QBO and ENSO signal.

Figure 4.7 shows the stability of association of the Congo convection and the zonal wind over South Africa. The cross spectrum modulus shows that the strong signals are in phase between 30-40 months and 40-60 months. The time delay between the two time series shows that the Congo convection is leading the zonal wind starting from 1974 to 1990 by 0-10 months. From 1990-1995 the zonal wind is leading by 0-2 months, and in the remaining period they are in phase as seen in the bottom panel.

4.6 Congo convection and NINO3 SST

It can be seen that NINO3 SSTs are leading the Congo convection in most of the cases (figure 4.8). The filtered time series for NINO3 SST show major peaks of positive anomalies in 1982/83 and 1997/98, related to El-Nino and, negative anomalies in 1988 related to La Nina. The annual cycles show amplified amplitudes during El-Nino and La Nina years. The modulus spectrum of NINO3 reveals major peaks in 1982/83 and 1997/98. The period of the main peaks varies from 2-6 years, is within the expected limits of ENSO.

Figure 4.9 Indicates the stability of association of the Congo convection and NINO3 SST. From the top panel the two series are in phase except that NINO3 is leading the Congo convection in most of the cases with an exception of a few periods. The cross modulus spectrum of the two time series show a strong signal with a period of 2.5-4.3 years in 1983/83 and 1997/98 which were El Nino years and 1987-96 which were La Nina years



Fig. 4.6 Zonal wind at 200 hPa over South Africa. From top left in a clockwise manner, time series of Congo convection and zonal wind, annual cycle of zonal wind, location of the area and the modulus spectrum of the filtered 1.5-16 years zonal wind.



Figure 4.7 Zonal wind at 200hPa over South Africa. From top panel time series of 1.5-16 yr. filtered Congo convection and the zonal wind, cross spectrum modulus and time delay curve between the two series.



Fig. 4.8. NINO3. From top left in a clockwise manner, time series of Congo convection and NINO3, annual cycle of NINO3, location of the area and the modulus spectrum of the filtered 1.5-16 years NINO3.

7



Figure 4.9. NINO3 . From top panel time series of 1.5-16 yr. filtered Congo convection and NINO3, cross spectrum modulus and time delay curve between the two series.

with Congo convection leading by 0-8 months as seen in the bottom panel. The upper zonal wind response to ENSO seems to be the main connection here.

4.7 Congo convection and QBO

Figure 4.10. show that in a good number of years, Congo convection leads QBO. The annual filtered data for QBO is symmetrical with almost a sine curve, with a frequency of 2-3 years which is a typical behaviour of QBO. The third panel shows the position for QBO, which covers the tropical area 5° either side of the equator. The fourth panel is the modulus spectrum for the QBO with a period of 2-3.5 years.

Figure 4.11 indicate the stability of association of the Congo convection and QBO.

From the top panel, for the period 1974-80, both time series are in phase with the Congo convection leading in most of the cases. The cross modulus spectrum indicates that both time series are in phase with strong association between 30-40 months (2.5-3.4 years), from 1974-84 and from 1990-98. The time delay indicates that the Congo convection leads the QBO by 0-8 months. In some months they are in phase. This suggests that equatorial convection may help to modulate the QBO.

4.8 Correlation analysis

The strength of association among variables is assessed by linear pair-wise and multiple correlation. The tool should be used with care because the method does not distinguish cause and effect. Hence it is possible to draw inappropriate conclusions. It can be noted that a correlation of zero value between variables may not necessarily imply that there is no relationship. This may be caused by differences between simple correlation coefficient that relates predictand to one of several predictors that influence it and partial correlation coefficients, which yield relationships between variables keeping others constant.

4.8.1 The PC rainfall within the bimodal rainfall area

Africa monthly average rainfall data from the University of East Anglia CRU gridded data at resolution 0.5 degrees, based in the domain 15°N-35°S is used for this analysis. An optimal 15 PC solution is utilized and rainfall indices are constructed from area averages. The data covers the period 1948-1998, a sample length of 600 months. A



Fig. 4.10. QBO. From top left in a clockwise manner, time series of Congo convection and QBO, annual cycle of QBO, location of the area and the modulus spectrum of the filtered 1.5-16 years QBO.



Figure 4.11 QBO. From top panel time series of 1.5-16 yr. filtered Congo convection and QBO, cross spectrum modulus and time delay curve between the two series.



continuous wavelet transform analysis was applied to the data, to filter out high frequency variability (periods <1.5 years) and to analyze the remaining slow cycles, that

Fig. 4.12 Africa PC rainfall. After Jury and Philipp(2002)

may be related to ocean atmospheric coupling and predictability. The analyzed PCs are shown in figure 4.12

4.8.2 Correlation between tropical bimodal rainfall indices and apriori predictors over selected key areas

Using the same data set as in section 4.2 covering the period 1948-1998 correlation analysis was done between PC rainfall indices over bimodal areas and global parameters over key areas. The key areas and the global parameters are shown in figure 4.13(After Jury, 2001). The selected key areas are:





catU = central Atlantic U wind 5°N-10°S, 50°W-0 naST = tropical north Atlantic SST 7-23°N, 18-24°W seaST = tropical southeast Atlantic SST 5°N-13°S, 13°W-11°E wiV = west Indian Ocean V wind, 5°N-10°S, 40-60°E ciST = central Indian Ocean SST 15°N-15°S, 50-80°E eiU = east Indian Ocean U wind, 5°N-10°S, 75-100°E

Table 4.1. 0 lag relationship between tropical bimodal monthly rainfall indices and global parameters with cycles(<1.5yrs) filtered out for the period (1958-1998, df = 41)

	Parameter	PC9	PC5	PC12	PC7	PC14
-		North	South	West	Kenya and	North Angola
		Congo	Congo	Congo	N.Tanzania	
1	CatU	0.07	0.11	0.27	0.14	0.25
	(5N 108,50W- 0)					
2	NaST	0.29	0.03	0.13	0.14	-0.06
	(7-23N,18-42W)					
3	SeaST	-0.03	0.01	0.32	0.08	0.21
	(5N-13S,13W-11E)					
4	WiV	0.19	-0.15	0.23	-0.08	0.24
	(5N-10S,40-60E)					
5	CiST	0.03	0.16	0.04	0.43	0.00

(15N-15S,50-80E)				
(5NI 108 75 100E)	· · · · ·	·	~~~~	
(JN-103,73-100E)				

The significant relationship between north Atlantic SST and PC9 (north Congo) rainfall is due to advection of moist unstable warm air from the Atlantic Ocean through west Africa to central Africa by westerly winds in the lower levels, particularly during JAS season.

Similarly relationship between southeast Atlantic SST and PC12 (west Congo/Angola) rainfall is due to advection of moist unstable warm air from the Atlantic Ocean to central Africa by westerly winds in the lower levels, especially during JAS and MAM seasons.

The significant relationship between central Atlantic zonal wind and PC12 (north Congo/Angola) rainfall is due to the east-west oscillation of the Walker circulation. During JAS season the ascending arm of the Walker cell is centred over the Congo basin while the descending arm is over the Atlantic Ocean. This scenario will force the zonal winds in the lower levels over the Atlantic to move eastwards to the Congo basin and Angola and they advect moist unstable warm air to central Africa. Similar results were obtained by Matitu (2001). According to Mpeta (2001), the westerly wind over Atlantic during JJA and SON seasons is negatively associated with the DJF rainfall over eastern ,central and west Africa. The relationship between central Indian SST and PC7(Kenya/North Tanzania) rainfall is due to advection of moist unstable warm air from the Indian Ocean to east Africa by easterly winds in the lower levels, especially during OND and MAM seasons.

The significant relationship between east Indian zonal wind and PC7 and PC5 (Kenya/north Tanzania and south Congo) rainfall is due to the east-west oscillation of the Walker circulation. During OND season the ascending arm of the Walker cell is centred near the coast of East Africa while the descending arm is over Indonesia. This scenario will force the zonal winds in the lower levels over east Indian Ocean to move westwards to east Africa and they advect moist unstable warm air to east and central Africa. Similar results were obtained by Matitu and Mpeta (2001). According to Mpeta (2001), the zonal winds over eastern Indian Ocean during SON and DJF are negatively associated with

DJF rainfall over east Africa, Angola and Congo. They are positively associated with DJF rainfall over southern Africa. Westerly winds induces an outflow from East Africa and hence divergence which results in reduced rainfall during DJF season.(Hastenrath, 2000). An easterly wind towards East Africa brings warm moist air and convective activities. In the SON, DJF and MAM seasons, positive zonal wind over east India key area is negatively associated with MAM rainfall over East Africa and positively with MAM rainfall over Mozambique, Zimbabwe and Zambia. Current research suggest that this wind induces ocean Rossby waves to travel westward across the Indian Ocean causing changes in SST that shift convection over Africa.

Autocorrelation and cross correlation for different indices was conducted to check for persistence, period of association and to assist in the determination of degrees of freedom to be used in correlation between global indices and PC rainfall. The significant correlations at 95% confidence limit (single tail) are highlighted in table 4.1.

Significant correlations, which have also been found by other researchers (Jury 1999, Mpeta 2001 and Matitu 2001) are, -0.55 between East Indian zonal wind and rainfall for PC7, 0.43 between Central Indian SST and rainfall for PC7, -0.34 between East Indian zonal wind and rainfall for PC5, 0.32 between South East Atlantic SST and rainfall for PC12.

4.8.3 Correlation between Congo convection(negative OLR over defined area 10°S 5°N 15°-30°E) and PC rainfall indices within the region together with known key predictors.

The Congo OLR data and the other parameters (which include PC rainfall and known key indices) used in section 4.3 covered the period 1974 -2000. A continuous wavelet transform analysis was applied to the data, to filter out high frequency variability (periods<1.5 years >16years) and to analyze the remaining slow cycles which are related to ocean atmospheric coupling and predictability. The number of months used was 324, which implies that with n=324 a correlation of 0.2 is significant at 95% confidence level. The results are shown in table 4.2 and significant correlations are highlighted.

Area	PC1	PC2	PC3	PC13	NINO3
	E. Sahel	Namibia	Guinea	Mozam.	SST
	.32	-0.35	0.27	-0.28	-0.27
Area	PC8	PC9	PC10	PC12	PC5
	W.Sahel	N.Congo	W.S.Afri.	WCongo	E.Congo
	0.33	0.19	-0.28	0.41	0.17

 Table 4.2 Zero lag correlation of Congo OLR with African rainfall and Ocean monsoon

 indices for the period 1974 -2000.

From table 4.2 it can be observed that there were significant correlations between Congo OLR and the following parameters.

-East Sahel 0.32, West Sahel 0.33. This implies that Congo convection spill over to the Sahel. The Congo convection acts as a driving force for the zonal easterly winds over this region which generates divergence aloft and hence inducing convergence in the lower levels particularly during JAS season.

-Namibian rainfall, -0.35, West South Africa rainfall -0.28, Mozambique and South Tanzania -0.28, Nino3 -0.26, all have a negative relationship with Congo convection. Hence at zero lag the southern African convection is anti-phase.

4.8.4 Correlation of seasonal Congo convection (Negative OLR) and seasonal JAS rainfall for PC's 1.3,8,12 for the period 1974-2000

 Table 4.3 Correlation of seasonal Congo convection (Negative OLR) and seasonal JAS rainfall

Congo OLR	PC1 -JAS	PC3-JAS	PC8-JAS	PC12-JAS
JAS- 0 lag	0.31	0.30	0.37	0.49
AMJ – 3months	0.17	0.32	0.25	0.48
JFM6months	0.06	0.33	0.11	0.39

The seasonal analysis shows that the best correlation is obtained between Congo convection JAS season and PC12 JAS rainfall. The correlations are significant for all the PC's at lag 0 and lead 1(AMJ season) and decrease at lead 2. However for PC3 and PC12 the Guinea coast and west Congo increased convection in the preceeding winter relates to strong monsoon in the following summer. This memory may be attributable to land-atmosphere interactions and is important for predictability.

4.8.5 Correlation of seasonal Congo convection(negative OLR) and seasonal DJF rainfall for PC's 2,13,10 for the period 1974-2000.

Congo OLR	PC2-DJF	PC13-DJF	PC10-DJF	
DJF 0 lag	-0.41	-0.35	-0.43	
SON -3months	-0.40	-0.56	-0.51	
JJA -6months	-0.33	-0.59	-0.48	

Table 4.4 Correlation of seasonal Congo convection(negative OLR) and seasonal

The seasonal analysis shows that the best correlation of -0.59 is obtained between Congo convection JJA season and PC13 DJF rainfall. The correlations are significant for all the PC's at lag 0, lead 1(SON season) and lead2 (JJA season). Hence increased rainfall over Central Africa occurs at the expense of the adjacent southern regions.

4.9 Summary:

DIF rainfall

In this chapter Congo convection (or negative OLR) was analyzed using the wavelet analysis method. Composite analysis using the Congo convective index for wet-dry years was used to identify circulation regimes. The parameters, which were significantly correlated with Congo convection were subjected to wavelet analysis to check the degree and stability of association. The relationship between equatorial rainfall to each other and to specific parameters over key areas of the Atlantic, Pacific and Indian Oceans was discussed. Then correlations between Congo OLR and other parameters within and outside the region were calculated using continuous and seasonal data sets to determine the best predictors for the rainfall. The best correlation was -0.55 for n= 600, between

East Indian zonal wind and East Africa PC7 rainfall, as found by other researchers, (Matitu et al, 2001). The western part of Congo PC12 had a correlation of 0.27 with the Atlantic zonal wind. Correlation between seasonal Congo convection(negative OLR) was significant JAS rainfall for PC 12, with a high correlation of 0.41. Correlations of Congo OLR and other parameters were worked out on seasonal basis in order to select a best correlation for analysis in the following chapters and to asses the impact of Congo convection to the surrounding area. Thus a conceptual model can be developed in which during JAS season we normally have westerlies in the lower levels over southeast and central Atlantic and these winds advect warm moist air to the Congo basin. figure 4.14 At the same time we have relatively dry southerlies from the southern part of Africa converging also into the Congo basin.



surrounding circulation.

Winds in the lower levels from the Indian Ocean converge with westerlies from the Atlantic Ocean over eastern part of the Congo basin on

the edge of the escarpment. As a result, during this period we have dry conditions over east and south Africa. Moisture and latent heat from the Congo basin is at the same time advected northwards by the monsoon winds and as a result the Sahel region receives rainfall in sympathetic mode with the Congo basin.

This chapter has therefore paved way for other chapters on time lag correlation analysis, composite analysis, model development, forecasting, conclusion and recommendations.

CHAPTER 5

LAG CORRRELATION PATTERNS WITH RESPECT TO CONGO CONVECTION.

5.0 Spatial correlation of Congo convection (inverted OLR) and other parameters.

5.1 Introduction

This chapter looks at the influence of the Congo convection on the surrounding areas: The Indian and Atlantic Ocean monsoons using correlation analysis with a focus on the rainy seasons MAM and JAS and their precusor seasons. The lags are overlapping because the influence of Congo convection is expected to be short lived compared to the influence of the nearby Oceans. The analyzed domain is from 35°S- 25°N, 40°W- 85°E. In a good number of cases most circulation patterns differ before, during and after a rainy season and this might assist in our understanding.

5.2.0 Spatial correlation of Congo convection and other parameters at MAM-2 to MAM+2

5.2.1 850hPa for MAM season zonal wind with Congo convection(negative OLR).

Congo convection was correlated with the zonal wind at MAM-2 to MAM+2 with n=324 months which implies that a correlation greater than 0.2 is significant. The monthly data covers the period 1974 to 2000. The spatial maps provide significant results (figure 5.1)

The zonal winds for the period January to March, which is lead 2 for MAM season, show significant negative correlation over Madagascar area and positive ones over northern Congo. This produces a cyclonic structure, implying that with easterlies over Madagascar, the Congo convection is enhanced and vice versa. A wavelike structure extends from the Indian Ocean around Madagascar, through the continent up to Brazil. A correlation >0.4 exists between Congo convection and the zonal winds over the area close to Madagascar while a correlation <0.4 can be observed over northern part of Congo extending to the Sahel region. At lead 1(February-April) the same pattern persists as at lead 2 except for the weakening of the correlations over north Congo and strengthening of positive correlations over west Africa. At lag 0 the main features are the positive correlations over Indian Ocean north of Madagascar and over the south Atlantic. The



Fig.5.1 Correlation between Congo convection(negative OLR) and Zonal wind at 850hPa MAM season. From top panel lead 2 (Jan. to March) to lag 2 (May to July) bottom panel

values over the Indian Ocean have changed sign and shifted northwards close to the equator. This implies that with the shift of easterlies northwards, it enhances the decrease of activity over Congo and the same applies to the south Atlantic relationship. The patterns are generally weaker after lag 0. This is the period of the southeast monsoon and most of the active weather has shifted northward and eastwards over the Indian Ocean and northwards over the Congo basin, in line with the mean position of the ITCZ in this period.

5.2.2 200 hPa for MAM season zonal wind with Congo OLR

Commencing at lead 2 (figure 5.2) the dominant feature is the strong negative correlation of the westerly winds with Congo convection. This implies that the upper westerly winds over south Atlantic encourages convective activity over the Congo, with gradual strengthening of the correlations from 0.4 to >-0.4 as we approach lag 0(MAM season). The relationship starts weakens after lag 1. This is the period when the convective activity has shifted northwards and the upper zonal winds have shifted from westerly to easterly over south Atlantic and we have significant negative correlations over Sudan. This implies a strengthening of westerlies which are associated with the south west monsoon.

5.2.3 850 hPa and 200hPa Meridional wind for MAM-2 to MAM+2

At lead2 significant positive correlations >0.3 are emerging over Brazil while a pocket of negative anomalies are emerging over the Indian Ocean at 70°E.(figure 5.3). At lead 1 significant correlations over Brazil have shifted eastwards and occupying an area between 30°W to 5°E touching West Africa and approaching the Gulf of Guinea. The patterns are weak from lag 0 to lag 2.

The correlation of Congo convection with the meridional wind at 200 hPa (figure 5.4). Starting at lead 2, significant correlation ≥ 0.4 are emerging the Guinea coast and over the southeast part of the continent. At lead 1 we have NW-SE axis of positive correlations and a similar axis of negative values<- 0.4 over the Atlantic Ocean. This is a pattern of a standing wave oriented in a NE-SW position because as we move to lag 0 the pattern is retained with a slight northeastward shift. The pattern diminishes fast as we move to lag1



Fig 5.2 Correlation between Congo convection(negative OLR) and Zonal wind 200hPa MAM season. From top panel lead 2 (Jan to March) to bottom panel lag 2(May to July)





Fig.5.3 Correlation between Congo convection(negative OLR) and Meridional wind 850hPa MAM season. From top panel lead 2 months(Jan. to March) to bottom panel lag2(May-July).



5

Fig.5.4 Correlation between Congo convection(negative OLR) and Meridional wind 200 hPa MAM season. From top panel lead 2 months(Jan. to March) to bottom panel lag2(May-July).

with only a few pockets of negative correlations. At lag 2 positive correlations are emerging over the Indian Ocean around 50°E and over the Gulf of Guinea. At the same time negative correlations are emerging at 85°E over the Indian Ocean. Hence a NW band of poleward flow over south Atlantic before and during increased Congo convection. This weakens the surface anticyclone and contributes to westerly equatorial flow.

5.2.4 Precipitable water for MAM season with OLR over Congo

From figure 5.5 it can be observed that at lead 2 we have significant negative correlations <-0.4 over the Indian Ocean extending to the East African coast. Negative values can also be observed close to the Brazilian coast. The area covered by negative correlations increases as we move to lag 0. Over East Africa, it is the period for the long rains over bimodal rainfall area. The relationship starts diminishing at lag 1 and ends at lag 2. Hence a dipole occurs whereby the West Indian Ocean convection and moisture is opposite to that of the Congo.

5.3.0 Spatial correlation of Congo convection and other parameters at JAS-2 to JAS+2

5.3.1 Corrrelation of the zonal wind at 600 hPa and 200 hPa for JAS-2 to JAS+2.

The 600hPa level has been selected instead of the standard 850 hPa because this level gave the highest correlation with Congo convection when a vertical section analysis was done. From figure 5.6, lead 2 a significant band >0.4 covers part of West Africa and extending to the Atlantic Ocean. The significant correlations extend from east Africa to Brazil through the Congo basin and West Africa at lead 1(June to August) . The maximum correlation is attained at lag 0 (JAS season). This is the period when convection matures over the northern part of Congo and the latent heat and moisture from Congo acts as a driving force to the zonal wind. At lag 1 (August -October) there is a reduction of the area correlated with Congo convection, where the only remaining area is confined over the coast of west Africa and a small pocket over the central Indian Ocean.

At lag 2 (September to November), negative correlations emerge over the Indian ocean and extend to east Africa. This is the period of north easterlies associated with the onset



Fig.5.5 Correlation between Congo convection(Negative OLR) and Precipitable water for MAM season. From top panel lead 2(Jan. to March) to lag 2(May to July) bottom panel



Fig.5.6 Correlation between Congo convection(negative OLR) and Zonal wind at 600hPa JAS season. From top panel lead 2(May. to July) to lag 2(Sep. to Nov.) bottom panel

of short rains over the bimodal region. The important feature here is the development of westerlies over the "bulge" of Africa prior to convection over the Congo.

5.3.2 Correlation of the zonal wind at 200 hPa for JAS-2 to JAS+2.

At 200hPa level, the correlation between zonal wind and Congo convection at lead 2, is characterized with the emergence of pockets of significant positive correlations south of India (figure 5.7). At lead 1 (JJA season) the significant correlations <-0.4 spread over east and central Africa and engulf the entire bimodal region. The same pattern can be observed at lag 0, where the area of negative correlations has increased and extend from the Indian Ocean to the Atlantic Ocean.

At lag 1 (ASO season), the significant correlations are around the coast of east Africa and extending to the Indian Ocean. Significant correlations are confined to the south of 15°S over the Atlantic Ocean extending over southern Africa.

5.3.3 850 hPa Meridional wind JAS-2 to JAS+2

From figure 5.8 the relationship between Congo convection and the meridional wind at 850hPa at lead 2 (May-July) shows an emergence of pockets of 0.3 correlation, over the coast of Angola and Brazil, while at lead 1 there are only a few pockets over Atlantic Ocean and over Brazil.

At lag 0 significant correlation is confined north of the equator in the Atlantic Ocean, close to West African coast. The same pattern occurs at lag 1 with the emergence of negative correlations over Brazil. The pattern changes at lag 2 (SON) season with a wide area with correlation ≥ 0.3 over Atlantic Ocean. There are also significant correlations emerging over the Indian Ocean at 70°E and over the horn of Africa. This is the period of the onset of the short rains over the eastern parts of Africa when northeasterly winds converge in the ITCZ. The meridional wind at 20W and 50E is positvely correlated with Congo convection. This implies that southerly flow at 20W and 50E are associated with enhanced Congo convection.

5 - 11



Fig. 5.7 Correlation between Congo convection(negative OLR) and Zonal wind at 200hPa for JAS season. From top panel lead 2(May. to July) to lag 2(Sep. to Nov.) bottom panel

5 - 12



Fig.5.8 Correlation between Congo convection(negative OLR) and Meridional wind at 850hPa for JAS season From top panel lead 2 months (May-July) to bottom panel lag2(Sept.-Nov).

5.3.4 200 hPa Meridional wind JAS-2 to JAS+2

At lead 2(May to July) figure 5.9 the only significant correlations are confined to southern Tanzania and northern Mozambique. The same pattern prevails at lead 1 with correlation <-0.3. At lag 0 (JAS season), only a small pocket of correlation is confined off the coast of Congo Brazzaville and Gabon. Pockets of positive correlations are emerging over the Indian Ocean at 60°E and over Brazil at lag 1. At lag 2 (SON season), significant correlations >0.4 are well established over the Indian Ocean at 60°E and over northern Atlantic close to Brazil. The wind response occurs after convection in the form of a wave train of northerly flows at certain longitudes.

5.3.5 Precipitable water for JAS-2 to JAS+2.

The correlation between Congo OLR and precipitable water at lead 1 and 2 is low with few pockets of positive and negative values as seen in figure 5.10. A small pocket of negative correlation is emerging over southeast Congo at lead 2. At lag 0 (middle panel) we have significant negative correlations extending in a SE-NW direction over the continent and close to the Brazil coast. The pattern strengthens at lag 1 and then weakens at lag2 with emergence of positive values over the Indian Ocean extending to East Africa. The relationship shows that during the peak of the monsoon period we have a positive correlation of Congo convection with precipitable water over central Africa and Sahel region.

5.4.0 Vertical sections N-S and E-W sections for significant cases.

North to South and East to West vertical sections of areas which have significant correlations with Congo OLR were analyzed and the sections are plotted for lead time of two months to lag of two months for each respective season.

5 - 14



Fig 5.9 Correlation between Congo convection (negative OLR) and Meridional wind at 200 hPa JAS season. From top panel lead2 (May-July) to bottom panel lag2 (Sep-Nov).



Fig 5.10 Correlation between Congo convection(negative OLR) and Precipitable water JAS season. From top panel lead2(May -July) to bottom panel) lag2(Sep-Nov).
5.4.1 Correlation of zonal wind in E-W vertical section at 5°N to 5°S from

60°W to 70°E with Congo convection for JAS

There is a significant correlation ≥ 0.4 extending from 60°W to 55°E and from 900 hPa to 500 hPa with a peak at 600 hPa. Between 30°-40°E and 50°W-60°W, the whole column from the surface is negatively correlated with Congo convection. Both are areas of descending motion.(figure 5.11).

At lead 1(JJA season) the correlation becomes stronger as well as the area coverage. The area of ascent extends to the Congo basin ($25^{\circ}E-40^{\circ}E$) and also over ($60^{\circ}W-40^{\circ}W$), from surface to 500 hPa. A similar case is observed at lag 0. At lag 0, a noticeable change is the emergence of negative correlations at around 150-200 hPa between 10°E to 70°E. This is the position of the tropical easterly jet. At lag1 (ASO season) the correlations decrease drastically and the only remaining significant correlations is at 200 hPa, from 40°E to 55°E. At lag 2 there are only few pockets of significant correlations emerging to the east of 50°E.

During the Asian monsoon, strong easterly flow of air develops in the upper atmosphere. This is centered on 15°N, 50°-80°E and extends from Southeast Asia to Africa. This easterly wind which lasts from June to early September is referred to as the tropical easterly jet. Best developed around 15km (150 hPa) above earth's surface with speeds in the core of the jet up to 40 ms⁻¹ over the Indian Ocean. The fact that the tropical easterly jet only occurs in the boreal summer suggests that its development is related to the seasonal cycle of convection and surface heating in the area over which the jet lies. The tropical easterly jet is formed because of the geographical contrasts in heating between the warm subtropical Asian landmasses and the relatively cool oceanic equatorial latitudes. The tropical easterly jet also occurs in the upper atmosphere, south of an area of upper anticylonic outflow, above mid summer Saharan heat low. Velocities in this part of the jet are lower by (around 25 m s⁻¹) than the Indian Ocean sector. Convergence within the jet over Africa creates subsidence, which plays a role in moderating the advance of the south west monsoon over west Africa. At the end of the northern summer, when the area of maximum surface heating moves southwards the tropical easterly jet over both India and Africa disappears. The tropical easterly jet is important for determining rainfall



Fig 5.11 E-W Vertical section for 5N-5S correlation between Congo convection(negative OLR) and Zonal wind for JAS season .Top panel lead 2 (May -July and bottom panel)lag2 (Sept.-Nov). Dark shaded areas show high correlation with Congo convection. Arrows show the direction of motion.

patterns in southern Asia and Africa. Rainfall at the surface has been found to be more to the north of the jet entrance in southern Asia region and south of the jet exit in the west Africa region (Hastenrath, 1985). The results here indicate a close association between Congo convection and TEJ strength.

5.4.2 Zonal wind MAM N-S Vertical section correlation with Congo convection at longitudes 10°W -20°W from 35°S to 20°N

Positive correlations are reflected at around 15°S while positive ones emerge to the south of 25°S (figure 5.12) (JFM) lead 2. At lead 1, correlations have strengthened and have a value of -0.6 at 200 hPa at 25°S. At the same time the negative correlations at around 10°S and at 400 hPa are still significant and maintaining the same area coverage. Pockets of negative correlations are also emerging between 10°-15°N. At lag 0 MAM season the negative correlations have strengthened and the entire column between 30°W to 20°W has a high correlation <-0.6 with Congo convection. The positive significant correlations are maintained in the same area as in lead 1. The negatively correlated column is extended northwards to 10°S from 30°S and the positive correlations have decreased considerably. This implies that the westerly winds are negatively correlated with Congo convection. and easterly winds locally positively correlated with Congo convection. This implies that subtropical zonal flow over the Atlantic is influenced by the Congo convection during MAM season.

5.4.3 Zonal wind MAM+2 to MAM-2. E-W Vertical section correlation

with Congo convection at latitudes 20°S- 35°S.

Negative correlations <-0.4 emerge at 50°W and a small pocket of negative values at 30°E (figure 5.13 lead 2, JFM) upper panel. At lead 1(February to April) the significant negative correlations have extended into the entire column and spread eastwards from 50°W to 10°W and at the same time the positive correlations have slightly enlarged in area coverage. At lag 0 (MAM season) the negative correlations are well established and strengthened in the entire column and extend eastwards to 0° longitude. A wide area is then covered with correlations <-0.6. The positive correlation, which was establishing at 25°E, has now diminished. At lag 1(April-June), the correlations have started to weaken and reduced in area of coverage. At lag2 (May to July), the negatively correlated signal



Fig 5.12 N-S Vertical section for 10W 20W correlation between Congo convection(negative OLR) and Zonal wind for MAM season. Top panel lead 2 (Feb-March) and bottom panel Lag 2 (May-July). Dark shaded areas are positively correlated with Congo convection.



Fig 5.13 E-W Vertical section for 20S 35S correlation between Congo convection(negative OLR) and Zonal wind for MAM season .Top panel lead 2 (Feb-March) and bottom panel) lag 2 (May.-July) . Dark shaded areas are negatively correlated with Congo convection.

has diminished. Hence easterly winds strengthen over the South Atlantic during increased convection over the Congo.

5.5 Summary:

The spatial patterns of the tropical Africa climate were analyzed by investigating the influence of the Congo convection on the surrounding area global circulation, using spatial correlation in a horizontal and vertical plane. Correlation analysis for zonal and meridional winds for MAM and JAS seasons with the Congo convection was evaluated for a lead of two months to a lag of two months.

The main findings are:

-Congo convection is enhanced when we have easterlies at 850 hPa over Indian Ocean close to Madagascar during MAM season.

-Congo convection is positively correlated with westerlies in the lower to middle levels with a peak correlation at 600 hPa over the Sahel region extending to the Atlantic Ocean. This implies that the westerlies feed moisture into the Congo basin and at the same time the Congo basin spreads moisture and latent heat to the Sahel region particularly during JAS season.

-During MAM season there is a dipole pattern between west Indian Ocean convection and moisture to that of the Congo.

- The results indicate a close association between Congo convection and the strength of TEJ(Tropical Easterly Jet) mainly during JAS season. The tropical easterly jet is important for determining rainfall patterns in southern Asia and Africa. Rainfall at the surface has been found to be more to the north of the jet entrance in southern Asia region and south of the jet exit in the west Africa region (Hastenrath, 1985).

-In the upper and middle levels, westerly winds over the Atlantic during MAM season are negatively correlated with Congo convection. This implies that subtropical zonal flow over the Atlantic is influenced by the Congo convection during MAM season.

-Easterly winds strengthen over South Atlantic during increased convection over Congo.

The next chapter discusses the influence of Congo convection on the monsoon circulation.

CHAPTER 6

CONGO CONVECTION AS A DRIVER OF THE AFRICAN MONSOON 6.0 Introduction

The objective of this chapter is to provide evidence of the impact of Congo convection on the African monsoon and vice versa. This information will help in understanding regional climate interactions and make better interpretation of the analysis that will follow.

6.1 The African Monsoon

The monsoon circulation over Africa differs from the Indian-East Asian system in the magnitude, thickness of flow and geographical coverage. In addition higher latitude air masses are less involved. Due to the shape of the African continent there are basic differences in the structure and the physical properties of the monsoon systems between West and East Africa.

In West Africa, the large continental area north of the equator contrasts with the tropical Atlantic Ocean. As a result the West Africa monsoon winds demonstrate a good deal of difference in their physical properties. In East Africa the continent stretches both sides of the equator, and contains meridional mountain ranges comprising the Great Rift valley. The Indian monsoon flow is inhibited from penetrating into the Congo basin and affects the east African climate. The maritime Mascarene and Arabian highs play a role in determining the strength of the confluent moisture transport. The St.Helena anticyclonic system over the south Atlantic exerts an influence on the moisture flux into the Congo basin with a meridional orientation at 30°E that has important consequences as outlined below.

The Guinea monsoon, which affects the Sub-Saharan zone of West Africa, is related to the seasonal behaviour of the quasi- permanent circulation of the eastern Atlantic. The heat low characteristics of the North African trough are more intense and contrasts in properties of air on either side of the trough are pronounced. The equatorial flow discontinuity undergoes a latitudinal displacement during the course of the year, reaching a more poleward position during the boreal summer. In the Northern Hemisphere winter, West Africa is under the influence of the northeast trade winds. These emanate from the semi permanent subtropical high pressure system, which establishes itself over North Africa during the northern winter. North-easterlies prevail to an elevation of about 3000 m and bring dry and stable air masses that carry dust particles from the desert regions where they originate. These are locally known as the Hamattan winds. During January the ITCZ extends from Angola to Madagascar. West Africa is dry then and convection shifts south of the Congo basin.

During July a thermal low pressure area builds up over the Sahara desert at 20°N. As a result the ITCZ moves slowly northwards to a position near 15°N, while the St. Helena anticylone builds over the cold water of the Benguela current. Consequently a considerable pressure gradient develops between the South Atlantic Ocean and north West Africa. In response, the southerly flows recurve to become a westerly monsoon flow over the Guinea coast. Further recurvature brings this flow into the Congo basin and enhances the transport of moist unstable air to northern parts of Africa.

The regions close to the equator experience rains throughout the year due to the ITCZ. The adjacent semi-arid desert may only get rain at the height of summer, while double peaked precipitation is the characteristic of the intervening latitudes. The subtropical high pressure belts and anticyclonic gyres of either hemisphere confine the domain of tropical circulation. From here the lower tropospheric trade winds emanate to meet with a band of highest surface energy and low pressure near the equator.

In the subtropical latitudes various jet streams are developed at different times of the year. The upper tropospheric subtropical westerly jet is a feature of the respective winter hemisphere and owes its existence to the convergence of poleward transport of angular absolute momentum in the Hadley cells. In this aspect the Congo convection plays a role by injecting latent heat in the middle levels. This latent heat is transported northwards by the upper limb of the Hadley cell.

The upper tropospheric easterly jet ~200hPa is confined to the boreal summer and is related to the thermal wind pattern associated with the heated sub-tropics and the cooler equatorial atmosphere. It is best developed in July and August extending from the Indian Ocean across Africa to the north Atlantic around 10°N. This jet exerts a control on the surface climate through divergence/convergence in the entrance/exit regions. (Figure 6.1).

The African easterly jet ~600hPa is also prevalent in the northern summer. It is associated with the hot desert air to the north and moist monsoon air to the south of the ITCZ. Figure 6.1 illustrates the meridional cross section of the troposphere over West Africa during August (after Leroux, 1973). The Congo convection plays a key role in the injection of latent heat and moist air into the formation and strengthening of the 600 hPa low level and upper easterly jets.

A meridional low level flow appears in northern summer at about 1 km above the coast of East Africa. Extending with a clockwise curvature from the southwestern Indian Ocean across the equator to the Arabian Sea. It is regarded as the backbone of the southwest monsoon circulation, drawing moisture from Africa to India. The core of the jet is best developed at a height of around 1500 m (850 hPa) where velocities reach 30 ms⁻¹ on some occasions in July with an average of 12-15 ms⁻¹. Its mean position extends from east of the north eastern tip of Madagascar to the Kenya coast, at which point it recurves in a north easterly direction to extend across the Arabian sea in the direction of western India (Findlater, 1977). The jet is an integral part of the northern summer monsoon circulation in the African Indian areas and is highly divergent and subsident in character.

The subtropical highs are the source of the trades and function as major centers of action for the tropical circulation. They are normally located furthest from the equator during their respective summers. They assume a western-most position in both hemispheres during northern summer. The trade winds represent the lower portion of Hadley cells. They accumulate moisture and energy below the trade inversion and carry it to the equatorial trough. Consequently the trades can be regarded as playing an important role



Figure 6.1 Location of the tropical easterly jet and the African easterly jet (upper panel) and the meridional vertical section over west Africa during August and the associated weather in N-S direction (lower panel). (after Leurox, 1973).

in global energetics. They also drive and respond to underlying E-W gradients in SST/velocity potential.

In general the monsoon area of the world is delineated in terms of the complete annual reversal of the meridional wind, thus encompassing the western Pacific, the Indian Ocean sector and much of tropical Africa. Over sub-Saharan west Africa during northern hemisphere summer, a deep moist air stream from the southern hemisphere replaces and undercuts the dry northeast trades originating from the Sahara. In this study the African monsoon region has been defined using the period April to August vector winds at 850 hPa, specific humidity at 700 hPa and convergence/divergence in the lower levels (figure 6.2). Areas that are most affected by the African monsoon are confined north of equator where we have strong convergence in the lower levels and specific humidity at 700 hPa is $> 6 \text{ g kg}^{-1}$.

In the Indian Ocean sector during the northern hemisphere winter, weak dry winds sweep from south Asia across the equator to the southern hemisphere. The northern summer monsoon is of importance as it removes moisture from east Africa. The establishment of the heat low over south Asia is instrumental in its development.

6.2.0 Relationship between Congo convection and the monsoons.

The MAM season in this study is regarded as the onset period for the monsoon and JAS as the mature monsoon period. During MAM season most of the rains are confined south of the equator except over West Africa (figure 2.1). During JAS season most of the rains are north of the equator with high rainfall of up to 12 mm day¹ over West Africa and over the Guinea coast.

6.2.2 Velocity potential at upper levels for MAM

The relationship between Congo convection and monsoons is elaborated using a composite analysis of velocity potential at upper levels for the wet-dry index in figure 6.3. Two centers can be observed at lead 2 (JFM season), which are strong negative values (divergence) in the Mozambique channel extending in a NW direction into the continent and positive values (convergence) over the Gulf of Guinea extending



Fig.6.2 Definition of African monsoon using April-August mean vector wind at 850 hPa (upper panel) and specific humidity at 700 hPa (lower panel). The shaded areas in the lower panel show areas of maximum specific humidity and the shaded areas in the upper panel indicate areas of convergence.



Fig. 6.3 Mean Velocity Potential upper level (WET-DRY) scenario for Congo convection for MAM season. Top panel is for lead 2 JFM, middle panel lag 0 MAM, bottom panel lag 2 MJJ. Units m²s¹

6 - 7

northwards to west Africa. In general the Indian Ocean is characterized with negative values. This suggests a NW-SE see-saw extending partially over the Atlantic Ocean.

At lag 0 (MAM) the center of action has shifted to Sudan and extends with positive values (convergence) to central Africa. Weak negative values are confined to the south East Indian Ocean. This is the period of the onset of the monsoon and we normally have convergence in the lower levels and divergence in the upper levels over Africa.

During lag 2 (MJJ) most of the continent is engulfed with positive values (convergence) particularly strong over south Sudan, northern Congo and western parts of East Africa. There is a noticeable NE-SW gradient close to the equator, which is in line with the monsoon pattern particularly over eastern part of Africa.

6.2.3 500hPa Vertical motion (Omega) for JAS-2 to JAS+2.

The relationship between Congo convection and monsoons is elaborated by using the composite analysis of vertical velocity (omega) at 500hPa for the wet-dry index. The vertical motion field indicates areas of subsidence (sinking motion) and ascent(rising motion) where diabatic heating is efficient.

Negative values (uplift motion) are evident over the continent extending from the Mozambique channel towards a NW direction (figure 6.4). Negative values are observed over the Indian Ocean between 60°-85°E and close to the equator. At lag 0 there is an expansion of area covered by negative values over the Congo basin and over the Indian ocean to the east of 50°E. This is the monsoon period and we have sinking motion over East Africa which amplifies the SW monsoon. The pattern changes at lag 2 (SON season) as the negative values over the Indian Ocean have moved westwards close to the East African coast. This is the onset of the north east monsoon associated with the short rains over East Africa. The negative values over Congo have shifted southwards and negative values have emerged to the south east of Madagascar. On taking a vertical section at 5°S from 40°W to 85°E it can be observed that a form of small scale Walker circulation is in operation at lag 0 to lag 2. There is alternating descending motion over the east Atlantic



201

15N

10N

5N EQ 5S 1QS 15S

205

20N

15N

5ħ

ΕQ

55

105

155

205 207

20N

15N

10N 5N EQ 5S

165 155

2015

١ÓW

-0.02

Fig. 6.4 Omega at 500 hPa for (WET-DRY) JAS season at monthly lags from top at lead 2 MJJ middle panel lag 0 JAS to bottom panel lag 2 SON Units Pascal/s

0.01

0

SÓF

0.02

ι<u>ά</u>ε

-D.01

at 0°E, ascending over Congo at 20°E, then descending over East Africa at 40°E and finally ascending at 70°E over the Indian Ocean.

6.2.4 Correlation of Velocity Potential at upper level and Congo convection(negative OLR) for MAM and JAS seasons

The relationship between Congo convection and monsoons is elaborated by the correlation between OLR and the velocity potential at upper levels (figure 6.5).

The MAM season represents the period of the onset of the monsoon, the rainy season over equatorial Africa. At this period the correlation with Congo convection is <-0.3 over the bimodal region of East Africa and extending to the Indian Ocean. During JAS season the correlation is <-0.4 and it covers East Africa. This is the dry season over East Africa due to subsidence from the upper levels and diffluence in the lower levels due to cross equatorial flow.

6.2.5 Correlation of SST and Congo convection

The Atlantic Ocean exhibits a delayed impact of ENSO mainly in SST anomalies, north of the equator. This has an influence on regional atmospheric dynamics, (Camberlin et al, 2001). As an example a warm ENSO event tends to result in strengthened trade winds over the tropical Atlantic and cooler SSTs. Atlantic SST play a key role in the interannual rainfall across much of west Africa, yet they seem to have little impact on the Congo basin.

On analyzing the correlation between SST and Congo convection for different seasons. It can be observed from figure 6.6 that for MAM season, significant negative correlations <-0.3 occur over a small strip of the east African coast and positive ones to the east of Madagascar and over a small area of south Atlantic. During JAS season negative correlations are confined over the Arabian Sea and a small portion of the coast of north west Africa. Significant positive correlations are found along a narrow strip of the western Atlantic coast. Hence the African Monsoon is enhanced by warmer adjacent Oceans.



Fig. 6.6 Spatial correlation of Congo convection and MAM season SST (monsoon onset) upper panel, JAS season SST(mature monsoon) lower panel.



• Fig.6.5 Spatial correlation between Congo convection and Velocity Potential at upper level during monsoon onset MAM season upper panel, and JAS (monsoon period) lower panel.

6.2.6 Correlation of Precipitable water and Congo convection.

During MAM season which is regarded as the onset of the monsoon, we have significant correlations <-0.4 over the western part of the Indian Ocean extending to the coastal part of east Africa (figure 6.7). During JAS season, the mature monsoon, a SE-NW axis of positive correlation >0.4 is seen.

Hastenrath, (2000) hypothesized that a tropical Atlantic Walker cell exists and influences the climate of Africa in MAM season, the onset period of the monsoon. However the equatorial overturning in the Atlantic Ocean sector is strongest in DJF when rains shift to southern Africa. ENSO involves an alternation of the equatorial Walker cells between two preferred states. During warm phase of ENSO the Walker cell ascending limb (where strong convection occurs) is over Madagascar (Lindesay, 1988b). The tropical troughs form a NW-SE orientation over the western Indian Ocean. During El-Nino the eastern part of Africa gets increased rainfall while over the Congo basin the rainfall is less. Figure 4.8 comparing Nino3 and Congo convection. This suggests a weak descending arm of the Walker cell over the Congo basin during El-Nino. Both Indian and Atlantic Walker cell overturning are modulated by ENSO (Jury et al., 2001), correspond with East-West gradients in sea surface temperatures.

6.3 Summary.

The relationship between Congo convection and various fields was assessed. The meridional winds play a key role in the injection of moisture into the Congo basin and transporting moisture and latent heat to other parts of the continent, which are much drier. JAS is a rainy season over the Congo basin and both meridional and zonal winds play a key role in moisture transport into the ITCZ. The SSTs for both Indian and Atlantic Oceans have a role to play in the generation of moisture which is transported into the continent. The overview given in this chapter highlights, the relationship between Congo convection(negative OLR) and the monsoon winds.



Fig. 6.7 Spatial correlation of Congo convection and MAM season precipitable water(upper panel) and for JAS season lower panel.

Therefore the key associations of the Congo convection and the monsoons are:

- The composite analysis for vertical motion at 500 hPa using (wet-dry) years index for Congo convection reveals a weak Walker circulation operating in the equatorial belt with an ascending arm over Congo and descending over east Africa and west Atlantic Ocean during JAS season.
- During JAS season there is a strong negative correlation <-0.4 at upper levels over east Africa with Congo convection. This scenario explains the subsidence over east Africa at this period.
- The SST's over Indian and Atlantic Oceans have a role to play in connection with convection in the continent. This is illustrated by a correlation <-0.3 between Congo convection and SST over the western coast during JAS season. The warm tropical Oceans help the African monsoon by its lateral coupling with the oceanic convection which is the driving force. Expansion of the monsoon area is possible with the warming of the Gulf of Guinea in JAS while the Indian Ocean cooling does not play much of a role due to subsidence there.</p>

CHAPTER 7

MODEL DEVELOPMENT AND RESOURCE IMPACTS

7.0 Statistical Modeling of African rainfall using Congo OLR as a predictor. Introduction:

Forecasting of seasonal rainfall is a serious challenge to climatologists all over the world in particular over the African continent where most of the countries depend on rain- fed agriculture. The poor state of the economies obliges them to maximize the use of available water resources for use in hydro-electric power. Dynamical and statistical seasonal rainfall forecasting are at an advanced stage on the global level and forecasting results are quite promising. Prediction is difficult for most African countries because of the resources required to conduct seasonal rainfall forecasting operationally, yet statistical modeling is within operational capabilities of most national meteorological centers in Africa.

In this chapter the relationship between bimodal rainfall and specific parameters in key areas over Atlantic, Pacific and Indian oceans are briefly discussed. Then Congo convection is used to predict other parameters within the region and outside the region. A model is developed to forecast specific rainfall over the region and cross validation is done on the model to check its usefulness

7.1 Model choice

There are several models used for prediction. The frequently used ones are the statistical model and dynamical or numerical model. In statistical modeling historical data is used to develop an emperical relationship between the predictand (one to be forecasted) and the predictor. Linear regression and probability models are examples of statistical models. The dynamical model is essentially the numerical weather prediction (NWP), which uses a set of differential equations with integration of the equations of motion and state. Computational power here is an important aspect. Examples of these are the general circulation model (GCM), the regional circulation model and the limited area model (LAM). Dynamical/statistical models are a combination of the above, such that model output statistics are used to generate the rainfall fields.

7.2 Regression analysis

The strength of association among variables is assessed by the linear pair-wise and multiple correlation. The tool should be used with care because the method does not distinguish cause and effect, hence it is very easy to draw inappropriate conclusions. It can be noted that a correlation of zero value between variables may not necessarily imply that there is no relationship. This may be caused by difference between simple correlation coefficient that relates predictand to one of several predictors that influence it and partial correlation coefficients, which yield relationships between variables keeping others constant.

Multiple regression is generally used in developing long range forecasting models (e.g., least squares). Correlations were performed in chapter four to identify predictors to include in the forecast models. A stepwise regression method is used within the Systat software package. Congo rainfall is the target predictand in most cases.

A multiple regression is of the following form:

R=a+bX+cY+dZ

Where R is the predicted Congo seasonal rainfall anomaly, a is a constant, b, c, d are the regression coefficients for the predictors X, Y, Z. The number of predictors is limited to three because with this number you should achieve a hindcast fit of over 40%. If the model fails to achieve this level, then confidence in its use must be limited. Using more predictors reduces the degrees of freedom and causes 'conflict' within the model (Jury et al., 1997). The f-value and the r^2 coefficient of variance, are employed to choose useful models that could be used operationally. In stepwise multiple regression the selection procedure here is forward to control the entry of variables into the model. Variables are entered with the aim of obtaining a model with high degree of fit with the least number of predictors. This procedure is recommended in model formulation especially if one is not sure which variables are likely to be included from the candidate pool. The forward selection procedure starts by adding the new variable with the highest partial correlation. The software package checks and compares at each stage to see whether the previously selected variables are still significant (and no co-linear) and if they can be replaced or

removed. The method has been used by many researchers in climatology. Jury (1997) used the method to develop multi-variate linear regression models for South African summer rainfall covering the period 1971-1992. Hastenrath et al. (1995) has reported on emperical studies and found the important predictors to be SOI, zonal wind over Singapore at 50 hPa, and SST in the southwestern Indian Ocean in respect to summer rainfall over southern Africa. Here models are also developed to use Congo convection to predict convection over other areas of the region.

Models which explain >40% of variance are cross validated for their reliability. This is done by blanking the first ten years and using the remaining to forecast them and then blanking the last ten years and using the rest of the years to forecast them.

Model validation is an important component of model construction (Mason, 1998). The reliability test seeks to reveal how the model might have performed in an operational situation.

Co-linearity in predictors corrupts models and is to be screened out particularly to eliminate conspiring El-Nino signals and reduce artificial skill (Jury et al., 1997). Consequently the identification of co-linearity in predictors is done in this study by calculating the variance inflation factor (VIF) as recommended by Chatterjee and Price (1977) and adopted by Hastenrath et al (1995). The predictors in each model are considered and each one of them in turn is regressed on the remaining predictors. According to Chatterjee and Price (1977) the presence of co-linearity is deduced when the value of VIF is >10. The independence assumption has been confirmed using the Durblin-Watson test for first order autocorrelation in the residual errors. What is required is the error term, which should be random. Negative autocorrelation exists if the Durblin-Watson statistic is increasing towards 4, while independence exists if the Durblin-Watson statistic is about 2. Values below 1.5 indicate positive auto-correlation and the model should be rejected. Correlation analysis has been used to establish association between Congo OLR and with other variables such as PC rainfall over the region, SST, QBO, NINO3, sea level pressure, surface, 850 hPa, 200 hPa zonal and meridional wind components. Fishers test is also applied to the final result of the regression analysis whereby it is known as the F-ratio, which is ratio of variance of the regression versus that of the residual. The higher the ratio the better the model.

7.3 Use of Congo OLR to predict rainfall over other parts of the region using a regression analysis method.

The Congo OLR monthly data in combination with other parameters for the period 1974-2000 was used and the PC rainfall data for the same period, were both used to work out seasonal values for MAM and JAS seasons. This implies that, for each year there is one value for each season. Multiple linear regression analysis was carried out with lead time of one season. The number of years used in this study is 25. With n=25 a significant correlation should be >0.32.

7.4 Model results for Ocean monsoon predictors

The best combination of predictors with Congo OLR to forecast JAS rainfall over the selected PC's are presented in a table 7.1.

Predictors	Predicting	PC1-JAS	PC3-JAS	PC8-JAS	PC12-JAS
Ocean	season				
monsoon			1		
EiU and	AMJ	0.17	0.55	0.25	0.57
Congo OLR	lead 1				
U700 WA and	AMJ	0.72	0.38	0.52	0.56
Congo OLR	Lead 1				
wiV and	JAS	0.43	0.46	0.38	0.61
Congo OLR	Lead 0			<u> </u>	
NINO3 and	AMJ	0.32	0.55	0.38	0.56
Congo OLR	Lead 1				
QBO and	JAS	0.34	0.30	0.45	0.50
Congo OLR	Lead 0				
U200 SA and	JAS	0.48	0.33	0.42	0.51
Congo OLR	Lead 0				
catU and	JAS	0.31	0.45	0.38	0.52
Congo OLR	Lead 0				
seaST and	AMJ	0.19	0.46	0.29	0.56
Congo OLR	Lead 1				

Table 7.1 Correlation of selected predictors to forecast JAS rainfall over selected north tropical Africa PC's (Figure 4.12).

The predictors which were combined with Congo OLR were:

CatU Central Atlantic zonal wind

10N 10S, 50W-0

SeaST South east Atlantic SST	5N-13S, 13W-11E
WiV West Indian meridional wind	10N-10S 40-60E
EiU East Indian zonal wind	15N-10S, 75-100E
U700WA Zonal wind at 700hPa over west Africa	5N-15N, 15W 15E
NINO3 East Pacific ocean SST	5N-5S 150-90W
QBO Zonal winds over the tropics at 30-50hPa	5N- 5S
U200SA Zonal winds over South Africa	20-30S, 10W 35E
CiST Central India SST	15N -15S, 50-80E
PC 1 East Sahel	5N -15N, 8-38E
PC 3 Guinea	0°- 10N, 5W-20E
PC 8 West Sahel	8N-15N, 10W-8E
PC 12 West Congo	8S-0°, 12-23E

7.4.1 Model results for Congo OLR as predictor

The best combination of predictors with Congo OLR was selected for forecasting PC 1 JAS rainfall. It was earlier found that Congo convection was leading zonal wind at 700 hPa over west Africa by 0-3 months (figure 4.4). It was also found that during JAS season, the correlation between Congo convection and the zonal wind had the highest correlation >0.4 between 700-600 hPa over west Africa (figure 5.11). Basing on the above findings we can conclude that Congo convection influences the zonal wind which has a strong influence on PC 1(East Sahel) rainfall. Therefore in this analysis the zonal wind is used to forecast PC 1 rainfall. The best the relationship was between zonal wind at 700hPa for AMJ season over west Africa and PC 1 JAS seasonal rainfall as presented below.

Y = 0.005 + 0.472 (AMJ U700). In this case the constant is too small and can be omitted and remain with only the zonal wind

Analysis of the relationship is presented in the table below:

N	r	r ²	F-ratio	P
25	0.72	52%	24.411	0.00

The above results show that the model can forecast PC1 JAS rainfall with a reasonable accuracy.

On selecting the first 17 years and generating a model to forecast JAS rainfall for PC1 using the zonal wind at 700 hPa over west Africa for AMJ season, the results can be seen in figure 7.1. The model is fairly stable and it predicts the rainfall with a reasonable accuracy as seen in figure 7.1.



Fig.7.1 Observed vs Forecast PC1(East Sahel rainfall) using zonal wind at 700hPa over west Africa for AMJ season as predictor. Model generated using the first 17 years(1974-1990)

On selecting the last 17 years and generating a model to forecast JAS rainfall for PC1 using the zonal wind at 700 hPa over west Africa for AMJ season, the results can be seen in figure 7.2 The accuracy of prediction is the same as in the above case and this confirms the stability of the model.



Fig.7.2 Observed vs Forecast PC1(East Sahel rainfall) using zonal wind at 700hPa over west Africa for AMJ season as predictor. Model generated using the last 17 years(1974-1990)

7.4.2 Models to forecast DJF rainfall over selected PC zones.

Table 7.2 Correlation of selected predictors to forecast DJF rainfall over selected south tropical Africa PC's.

Predictors	Predicting	PC2-DJF	PC10-DJF	PC13-DJF
Fill+Congo OLR	DJF	0.35	0.52	0.44
ciST+Congo OLR	DJF	0.38	0.48	0.26
OBO+Congo OLR	SON	0.41	0.24	0.35
NINO3+Congo OLR	JJA	0.45	0.56	0.31
U200 SA+Congo OLR	JJA	0.40	0.15	0.38

From table 7.2, it can be observed that on combining Congo OLR with other parameters, it enhances the relationship and hence the predictability of DJF rainfall over the selected PC's. In the above case the highest multiple correlation of 0.56 was obtained between West South Africa (PC10) DJF rainfall and a combination of NINO3 SST and Congo OLR.

7.4.3 Model for forecasting DJF rainfall over PC10(West South Africa)

The best combination of predictors with Congo OLR was selected for forecasting PC 10 DJF rainfall. The second predictor in this case is NINO3 SST. Congo OLR for SON season has been used in combination with NINO3 SST to forecast PC10 rainfall for DJF season. The general equation of the relationship between NINO3 SST with Congo OLR is, Y=.007+.121(SON OLR)-.366(NINO3 SON)

Test of the relationship is given in the table below

<u>N</u> .	 r	r ²	F-ratio	Р
24	0.56	31%	4.665	0.02

The above results show that the model can forecast PC10 DJF rainfall with a reasonable accuracy. On selecting the first 16 years and generating a model to forecast DJF rainfall



Fig. 7.3 Observed vs Forecast PC10(West S.Africa DJF rainfall) using Congo OLR and NINO3 SST SON season as predictors. Model generated using first 16 years(1974-1989) for PC10 using the selected predictors for SON season, the results can be seen in figure

The model is fairly stable and it predicts the rainfall with a reasonable accuracy as seen in the figure 7.3.

On selecting the last 16 years and generating a model to forecast DJF rainfall for PC10 using the selected predictors for SON season, the results can be seen in figure 7.4 The accuracy of prediction is the same as in the above case and this confirms the stability of the model.



Fig. 7.4 Observed vs Forecast PC10(West S.Africa DJF rainfall) using Congo OLR and NINO3 SST SON season as predictors. Model generated using last 16 years(1983-1989).

From the models we can deduce that they are fairly accurate in predicting DJF rainfall and the Pacific SST's have three times more influence on the rainfall than the Congo OLR.

7.5 Social economic impact and physical resource levels

7.5.0 Impacts of climate on social-economic and physical resource levels

7.5.1 Introduction

From model analysis it was found that Congo convection (negative OLR) was leading the zonal wind in the lower levels over west Africa and the zonal wind was found to be the main determinant of the rainfall over east Sahel. It was also found that a combination of Pacific SST with Congo OLR was able to forecast west South Africa rainfall within a reasonable accuracy. From the model, Pacific SST accounted three times more for the rainfall than Congo OLR. From the above findings we can conclude that Congo convection has a significant influence on rainfall in the surrounding countries that rely on rain fed agriculture. It is expected that climate will be of value to sustainable economic growth in these times of increasing pressure on the earth's limited resources. Current improvements in the global climate observing system have been made with increasing satellite technology and advances in climate modeling. Institutional systems are now being developed to exploit these advances in support of sustainable development, through a reduction of risks associated with extreme climate events. Climate information is now being applied directly and indirectly to many developed countries to a wide range of activities, including agricultural practices, resource management, economic planning, international relations, hydrology and health. Jury (2001).

In this study the impact of Congo convection is considered to have a major affect on the nearby countries. Most of the countries surrounding the Congo basin depend on subsistence agriculture to meet the basic needs for its population in excess of 100million with an expectation of reaching over 200 million by 2025(World population UNFP report 2001). It is estimated that more than half of the GDP(Gross Domestic Product) and three quarters of all jobs are attributable to rain fed agriculture. (Hulme, 1996).

The fundamental role of climate for the fate of mankind is increasingly being recognized at both international and national levels. Rainfall is the lifehood of most of the tropical areas and the seasonal distribution of rainfall regulates the agricultural calendar. The rainfall variability from year to year is the main factor responsible for fluctuations in crop yields and the related risks of production (Nieuwolt, 1986). Many parts in the tropical areas are semi arid and rainfall is extremely variable and often unreliable. A poor year can result in large-scale crop failure, food shortages and extreme cases of famine. Trees and grasses wilt and die and animals perish from hunger and thirst. Subsistence farming which provides most of the region with their food, depends on sufficient rainfall.

Drought is associated with suffering and loss of valued crops, livestock and wildlife. Praying for rain is not uncommon in many parts of tropical Africa and the onset of the rains is often viewed as the single most important event of the year. Droughts are not easily predicted and most of the tropical areas have long dry spells every year. If the rains do not come by a particular time, this may be a sign of drought and early rains may hide an impending drought. Some of the recent examples are: in Mozambique in 1982-83 the drought was the worst in 50 years, leading to thousands of deaths. During this period the Congo basin had below normal convection. In the dry summer of 1992 areas surrounding Kgalagadi in Namibia, the savannas of Angola, Botswana and the pastoral areas of southern Africa were desiccated. Drought left most of those areas parched and gasping for elusive rains. Most of the droughts were associated with El-Nino. During the above stated years, Congo basin had below convection and hence there was reduced moisture and latent heat to distribute to other parts of the region.

Though droughts in tropical regions are regular climatic events, there are other factors, which affect weather patterns. Deforestation and overgrazing caused by human activities results in low evapotranspiration and may prolong the drought and intensify dry spells occuring naturally within the climate.

Drought has its impact on water supplies. Lack of water affects every aspect of environmental health and human activities, including agriculture, natural areas, industry and development projects. Agriculture is most directly affected by drought and the impact can be extreme in dry land farming areas, which rely on rain to provide water for crops. Some classical examples are: In Botswana crop production fell from 60,000 tons to below 20,000 tons due to lack of rainfall in 1984, and production was as low as 7000 tons as the Kalahari desert encroached. This represented a food decline from 715 to 100 Kg per family as a result of drought. In 1984 Congo basin had below convection. This is a common phenomenon in most tropical African countries. In arable areas, problems of soil erosion are intensified and worsened during a drought. This is basically due to severe loss of vegetation during a dry spell. SARDC report (1994).

Drought is the most important factor limiting livestock production in tropical Africa. A drought lasting more than two to three seasons has a devastating effect on herds i.e. in Botswana drought reduced cattle numbers from 1.35 million to 900,000 in the dry years 1964-67. The 1991-92 drought killed more than one million cattle in Zimbabwe and many more in other countries of the southern highlands region. During the above periods, Congo basin had below normal convection and thus reducing the supply of moisture and latent heat to most parts of the region which implies, rainfall reduction and hence drought. During a drought, overgrazing leads to further degradation of pasture and shrinkage of arable land in rangelands. The deterioration of grazing capacity further reduces livestock numbers. In drier areas, scanty rainfall for a few years can kill vegetation permanently and poor land practices make it worse. In Namibia, degradation of pasture is caused by interaction of overstocking and drought cycles. Drought can also exacerbate deforestation, as some of those, whose crops are lost, attempt to make money by selling firewood. In Botswana, where cattle production constitutes a major economic base, a decrease in cattle population is a great loss. Rural people depend on their cattle for food and draught power. Loss of cattle forces them to hire tractors, which most cannot afford. In 1988-89 when the rain came, most of the communal farmers had no draught power because their herds had been destroyed by the drought. Ellis et al (1993). During 1988/89 the Congo convection was above normal.

Drought also affects urban areas and industry. Some examples are; in mid 1980's drought, the construction industry in Botswana was forced to reduce its activities after water reservoirs fell to critical levels. Beverage companies, which use a lot of water to wash bottles, had to change to non-returnable aluminum cans, which require less water. The 1992 drought in Botswana, the textile industry had to retrench workers after operations were scaled down due to a shortage of water. As a result, 50% of the workforce was laid off. Campbell (1994).

Droughts can have serious impacts in a war situation where normal relief mechanisms cannot operate. Armed conflicts like the situation in Angola and Congo, together with drought can lead to serious environmental abuses as people struggle to survive.

Historically droughts have produced an impetus for mass migration of people in tropical Africa. People tend to move from an adversely affected area to a relatively better one. In Botswana in 1991-92 season, people moved eastwards from rangelands to arable lands and eventually to urban areas.

Droughts over tropical Africa have been studied by many researchers. It is therefore important to plan for drought. Mismanagement of one drought leads to reduce productivity and greater susceptibility to the next drought. Awareness, education, training and accurate forecasting can help reduce drought susceptibility to the next drought. Therefore early awareness capabilities need to be upgraded in the region and improvement of information system. Collection and dissemination of information can play a key role in drought anticipation and preparation.

Floods have affected many eastern areas in tropical Africa. i.e. 1997 El-Nino in East Africa. During 1997/1998 Congo convection was below normal while East Africa had above normal rainfall and this suggests that East Africa has an opposite response to that of Congo basin. The floods damage crops, infrastructure and loss of life near rivers below the eastern escarpment. In Tanzania, the 1997/98 El-Nino had a significant impact because the rains flooded farms and destroyed crops. Roads, railways, and electricity

supply were destroyed resulting in disruption of communication. The country had to import 800,000 tons of maize to fill the gap. The total loss due to crops and infrastructure damage was estimated at 3 million dollars. Cases of malaria increased significantly. According to Sachs (2002) report released by WHO, May 2002 in Abuja conference, there was a clear evidence that malaria obstructs overall economic development in Africa. Malaria accounts for nearly one million deaths each year in Africa, an estimated 700,000 of these deaths are children. Since 1990, the per person GDP in many sub Saharan African countries has declined, and malaria is an important reason for the poor economic performance. According to the report, malaria slows economic growth in Africa by 1.3% each year. This slowdown in economic growth due to malaria is over and above the more readily observed short run costs of the disease. The sub-Saharan Africa's GDP is around \$300 billion and the short term benefits of malaria control are estimated at between \$3 billion and \$12 billion per year. The report also found that the cooler, malaria free countries at the northern and southern fringes of Africa average three times higher GDP per person than malarious countries, regardless of government policy, geographical location and other factors which impact on economic well being. Secondly one healthy year of life is gained for every \$1 to \$8 spent on treating malaria as a cost effective public health investment.

7.5.2 Climate and economic change in rural tropical Africa.

About two thirds of the African continent is comprised of dry lands and is considered highly vulnerable to climate change and variability. Southern Africa is among the most vulnerable regions in the world and therefore climate variability can have considerable impacts on the hydrology of the region and consequently on agricultural production. In semi-arid tropical regions, inter and intra-annual variability of rainfall, are key climatic elements that determine the success of agriculture. As the population is increasing there will be a need to increase food production in order to reduce the food import dependence,

Responding to climate variability is of immediate concern to Africa given its variable climate and reliance on natural resources in economic activities. At the same time global and national economic changes since the 1980's are altering the context in which farmers throughout southern Africa are dealing with climate variability. Southern Africa is currently experiencing dramatic economic changes, including globalization of economic activity through liberalization of trade and investment and regional trade integration. This has been coupled with spell of good rains 1996-2001.

Economic globalization and liberalization have differential effects on vulnerability at several levels in Africa, within a country and between households in a village. To secure sustained economic growth and poverty alleviation in the face of economic uncertainty, there is need to put measures in place for adaptation within the context of economic change.

African farmer responses to climatic events have been seen as belonging to a different sphere from economic reform, involving diversification in informal sector activities rather than the specialization and economies of scale in the formal sector. Refer to figure 7.5 for the GDP contributions for South Africa and Botswana. In order to assess how climatic and economic changes affect farmers, analysis must be carried at regional, national and village levels as analyzed by Jury (2001).

Because agriculture is a key sector in Africa, effects of liberalization measures will be felt profoundly within this sector. Potential impacts of liberalization for agriculture in southern Africa will include shifts in cultivation patterns toward cash crop exports, improved access to advanced technologies including drought-resistant seeds, and better success to credit for farmers.

7.5.3 A brief analysis of selected cases of impact of climate to the economy.

The economy of most of the countries in the region is dependent on agriculture and agriculture in these countries depends on rainfall. Countries in southern Africa which are influenced by the Congo convection, depend on subsistence agriculture to meet the basic needs of its population of more than 100 million so that other activities in service and industrial sectors can be healthily engaged in. The GDP for most of the countries depends on agriculture as seen for a few selected cases in figure 7.5. The rainfall pattern over
some countries are partly affected by Congo convection as the ITCZ moves either side of equator. It appears to spread convection northward and inhibit convection southward.



Fig. 7.5 GDP Contribution for selected countries which are partly affected by Congo convection.

7.5.3.1 Zambia case study

During the 1992 drought the GDP of Zambia declined by 9%, Zimbabwe 8% and South Africa 3%(Benson and Clay 1994), which contributed to rising unemployment (>30%) and economic stagnation. The Zambian economy, which recorded 6.5% growth rate in 1996, is estimated to have registered a growth of 4.6 in 1997 slightly higher than the population growth rate. However this is still an improvement over 1991-93 dry spell when the average per capita GDP declined by 3.6% (World Bank report 2002). The main reason for the decline in 1997 was poor performance in agriculture. Agricultural production fell from 15% in 1996 to 3.4% in 1997, due principally to variable rains associated with ENSO, which damaged crops. Maize (the country's staple diet), production which is the country's staple diet declined by 32% in 1997. During the period 1991-93 and 1997 convection over Congo was below normal and this deprived moisture and latent heat to the surrounding regions. The 1997 ENSO event was an exceptionally strong because it generated rainfall even over areas which were expected to be dry like Zambia, when such an episode occurs. The contribution to GDP for the Zambia economy shows that, agriculture at 32% is nearly equal to services and industry at 38% and 30% respectively as seen in figure 7.5.

7.5.3.2 Tanzania case study:

Agriculture is the backbone of the Tanzania economy whereby the sector accounts for an average of 50% of GDP and constitutes 50% of the export earnings. See figure 7.5. Manufactured goods contribute 11%, Minerals 19%, Petroleum products 2% and other exports 18%.

The livestock sub-sector in particular is an integral part of Tanzania's economy. According to 1994/95 Agriculture Census results, the sub sector contributes about 18% of the national GDP. The sub sector as a whole contributes about 30% to the agricultural GDP and provides food, which is consumed in the form of meat, milk, mile products and eggs.

Tanzania's climatic growing conditions are favourable for the production of a wide range of fruits, vegetables and flowers. The most important fruits include pineapples, passion fruits, citrus fruits, mangoes, peaches, pears and bananas, while vegetables include tomatoes, spinach cabbages, and okra. Flowers include tropical and non-tropical varieties. The external market of fruits and vegetables presents good opportunities in the neighbouring countries, Middle East and Europe. Oilseed crops include both industrial (castor seeds) and edible oilseeds (sunflowers, groundnuts, sesame, copra, cottonseeds and soya beans).

Spices such as black, sweet and hot peppers, chillies, ginger, onions, coriander, garlic onions, hermeric, cinnamon, and vanilla are important crops for both the domestic and export markets. The cocoa bean crop is a good small-scale foreign exchange earner and is also an important source of income to smallholder cocoa producers. Dates, kapok and oil palm are also produced.

Major staples (maize, rice and wheat), drought resistant crops (sorghum, millet and cassava) and other substaples such as irish potatoes, sweet potatoes, bananas and plantains are also produced.

Annual domestic consumption of sugar is estimated at about 300,000 tones (1996) and installed plant capacity is 230,000 tones p.a. However, actual sugar production averages around 120,000 tones per annum.

Main cash crops in Tanzania are:

Coffee: the top export crop is both a small holder and plantation (estate) crop and contributes 17% of Tanzania's foreign exchange earnings.

Cotton, the second biggest export crop, is mainly a small holder's crop and contributes 14% of country's foreign exchange earnings.

Cashew, the is the third most important export crop, is mainly a small holder crop and contributes 14% of the total value of Tanzania's foreign exchange earnings.

Tea is an estate crop which contributes 6% of Tanzania's traditional agricultural exports.

Tobacco is mainly a small holder crop and contributes 2% of export earnings

Sisal is essentially an estate crop, which contributes 1% of Tanzania's foreign exchange

Palm is a small holder crop and it is an important source of edible oil. The palm oil industry is generally underdeveloped with an average production of only 6,000 tons of palm oil per year.

Relationship between rainfall and maize yield in Tanzania.

Maize is one of the main food crops in Tanzania and most of the maize depends on



Figure 7.6 Relationship between maize yield and rainfall in Tanzania(1986-2002)

rainfall. An index for JFM rainfall for southern Tanzania, which covers unimodal rainfall area, was evaluated. The same index was evaluated for northern Tanzania for MAM season (bimodal rainfall area). These seasons give useful rainfall for the growth of maize. Both indices were combined to form one index and then correlated with maize yield data. The data used covered the period 1986-2001. See figure 7.6. A significant correlation of 0.41 was obtained between the two parameters for the period 1986-2002 and from regression analysis, it shows that rainfall explains 16% of the variation in maize yield. The El-Nino rains of 1997/98 destroyed most of the crops due to excess rainfall which caused floods and that is why the graph shows a decline in yield despite the fact that rainfall was high. During the same period Congo convection was below normal. A conceptual model can be formulated to forecast maize yield starting from a known predictor for rainfall over Tanzania, like the East Indian zonal wind at a lead of two seasons.(figure 7.7). A model using MAM season zonal wind showed a potential for

predicting maize yield in advance.(figures 7.8). A better model can be obtained when data for more years is available.



Fig 7.7 Conceptual model relating east Indian zonal wind and maize yield in Tanzania.



Figure 7.8 Relationship between maize yield in Tanzania and and the zonal wind zonal wind for MAM season over east Indian Ocean.

Relationship between GDP and rainfall

An index for JFM rainfall for southern Tanzania, which covers unimodal rainfall area, was evaluated. The same index was evaluated for northern Tanzania for MAM season (bimodal rainfall area). These seasons give useful rainfall to both food and cash crops. Both indices were combined to form one index and then correlated with annual GDP growth rate. The annual GDP data was detrended. The data used covered the period 1986-2001. Significant correlation of 0.45 was obtained between the two parameters.



Fig.7.9 Comparison of GDP annual growth rate and an index of January to May rainfall over Tanzania. The variance explained r² value for 1980-2000 was 20%.

From regression analysis, it shows that rainfall explains 20% of the variation in yield. From figure 7.8 it can be observed that the rainfall is well in phase with GDP growth rate between 1980-89. Due to change in economic policies and inflation, there was a change in the relationship between growth rate and rainfall from one decade to another. Despite change in economic policies and inflation, there is a reasonable relationship between the two parameters. Clearly crop production is a critical element in human health and engagement in economic activities.

7.6 Summary

In this chapter models were developed to forecast JAS seasonal rainfall over central Africa. The best model was obtained by linear regression analysis between zonal wind at 700hPa over west Africa with PC 1 rainfall. Congo convection was found to lead the zonal wind. A correlation of 0.72 was obtained, which explained 52% of the rainfall variation over the East Sahel region at zero lead time. Models were also developed to forecast DJF rainfall. The best model is the combination of Congo OLR (an index of Congo convection) and NINO3 SST with DJF rainfall over PC10 (West South Africa). A correlation of 0.56 was obtained, which explained 31% of rainfall variation. The results show that Congo convection has a significant influence on the rainfall pattern in the sub-region. The impact of rainfall on the economy and physical resource levels has been analyzed using examples from Zambia, and Tanzania. The results show that there is a significant relationship between GDP growth rate and rainfall. Congo convection has a significant result that requires further study with numerical models.

CHAPTER 8

SUMMARY AND CONCLUSION

8.0 Introduction

Rainfall is one of the major components of climate system, which supports a number of socio-economic activities in most African countries which depend on rain-fed agriculture. The spatial and temporal distribution of tropical Africa rainfall varies considerably from year to year. Floods and droughts cause disruptions leading to food shortages. A depletion of savanna productivity in Tanzania causes wild animals to migrate away from their normal habitat, leading to loss of revenue in the tourism sector. The floods of 1997/98, disrupted agricultural activities and destroyed food and cash crops, and infrastructure losses amounted to US\$76 million, (F.Tilya, personal communication., 2002). Due to the variable nature of rainfall over tropical Africa and the dependency of countries on rain water availability, planners should take into account the vagaries of climate of Africa in order to mitigate the impacts.

In many studies year to year fluctuations of seasonal rainfall are a concern to the community but at the shorter time, flash flood warnings can be useful. In this study the influence of Congo convection on the surrounding regions was investigated at a time scale of one to four months.

Although studies on rainfall variability over Africa at different time scales have been conducted and global teleconnections found, few emperical studies have been done on the interaction of Congo convection with the surrounding climate system. An attempt is therefore made to create this understanding locally.

Seasonal rainfall over many areas of Africa is modulated by global oceanic and atmospheric phenomena (ENSO, QBO) through the manner of 'uptake' in regional thermodynamic and circulation patterns. In this study effort has been made to identify and document spatial and temporal patterns using an index of Congo convection, namely negative OLR. Congo convection was correlated with other parameters within and outside the region. Models were developed to forecast African rainfall of climate using Congo convection as a predictor. A brief analysis of the impact of climate on the economy of selected African countries was done.

In this study different data sets and methods of analysis have been used. A recently introduced technique, the Wavelet Transform (WT) was employed to study spectral characteristics at different time series. This method has an edge over the Fourier technique, as it is possible to study instantaneous frequency characteristics of a time series and can also be used to filter a time series in a particular frequency.

A summary of findings from this study is made below.

8.1 Summary of Chapter 3

- During JAS season when there are wet conditions over the northern Congo and dry conditions over East Africa. The vertical and the zonal wind patterns indicates the prescence of a Walker circulation.
- A north-south vertical section through Congo basin for MAM season shows strong easterlies at 5°N at 600 hPa level and westerlies at 200 hPa level at 20°S and 15°N. The 600 hPa level depicts the African easterly low level jet stream and the 200 hPa level, the westerly jets.
- During JAS season the main pattern is the strong easterly jet which extends from India to Africa at 150 hPa at 10°N and a westerly jet to the south at 15°S. The jet streams have a significant influence on weather at the entrance and exit points.

The east -west section of the zonal wind during MAM season depicts convergence of low level westerlies from the Atlantic Ocean with easterlies from the Indian Ocean at 30°E. This is where the Congo basin rises to form an escarpment with East Africa. This is the area of highest rainfall in the Congo.

□ During MAM season the vertical meridional pattern reveals a shallow overturning circulation between 0°- 12°N and 15°- 25°E where we have relatively strong westerlies at 950 hPa and easterlies at 650 hPa. An overturning circulation is important for the transport of moisture and latent heat in the upper atmosphere.

- During JAS season for the meridional vertical section at 40-50°E, winds with speeds greater than 10ms¹ are well emphasized with the establishment of the SW monsoon and the East African low level jet.
- □ When gauge rainfall data was compared to satellite estimated rainfall, it was found that satellite techniques tended to overestimate rainfall. Satellite data is useful in covering areas with few rain gauges particularly over the Congo basin. Areas with rain gauges should exploit the opportunity to calibrate satellite retrievals for practical use.

8.2 Summary of Chapter 4

This chapter deals with the temporal variability of African monsoon indices and the main points were:

Wavelet analysis was applied to Congo convection time series and the modulus spectrum revealed cycles of 2-3 years and 3-8 years.

The results for cross wave analysis between Congo convection and selected parameters are listed below.

- The 700 hPa zonal wind over West Africa is in phase in 2-4 year periods (QBO) and 4-8 years (ENSO). The time delay curve shows that the Congo convection leads the zonal wind, which indicates that Congo convection is one of the driving forces of the Atlantic Walker Cell.
- South African 200 hPa zonal wind was always in phase with Congo convection. The modulus spectrum shows cycles of period of 2.5-5. The Congo convection was always leading the zonal wind by 0-10 months. This suggests that Congo convection is one of the driving forces of birfurcation of the southern jet stream.
- QBO was found to be in phase for most of the time with the modulus spectrum revealing cycles with a period of 2.5-3.4 years with the Congo convection. Congo convection was leading QBO by 0-8 months. This suggests that Congo convection is one of the sources of energy for the QBO.
- □ NINO3 was found to be in phase for most of the time with the modulus spectrum revealing cycles with a period of 2.5-4.3 years with the Congo convection. NINO3

was leading Congo convection by 0-8 months except for a few years. When the Pacific is warm the convection is weaker.

- Significant correlation at 95% confidence between predictors and PC rainfall over central Africa are,
- □ -0.34 between East Indian zonal wind and rainfall for PC5 (South Congo)
- 0.32 between South East Atlantic SST and rainfall for PC12 (West Congo, Gabon and Cameroon)
- **0.29** between North Atlantic SST and rainfall for PC 9(North Congo)
- Correlation between Congo convection and PC rainfall indices in tropical Africa, showed a positive relationship with the Sahel and a negative relationship with southern Africa.
- Correlation between Congo convection and PC rainfall at seasonal level in tropical Africa indicated a potential for using Congo convection to forecast rainfall over the PCs at a lead time of one season.

8.3 Summary of Chapter 5:

The results of spatial correlation of Congo convection, with other parameters at lead to lag two months was provided. The data covered the period 1974-2000, hence significant correlation are >0.32.

The main findings are:

- Congo convection is enhanced when we have easterliesat 850 hPa over Indian Ocean close to Madagascar during MAM season.
- Congo convection is positively correlated with westerlies in the lower to middle levels with a peak correlation at 600 hPa over the Sahel region extending to the Atlantic Ocean. This implies that the westerlies feed moisture into the Congo basin and at the same time the Congo basin spreads moisture and latent heat to the Sahel region particularly during JAS season.
- During MAM season there is a dipole pattern between west Indian Ocean convection and moisture to that of the Congo.
- □ The results indicate a close association between Congo convection and the strength of TEJ(Tropical Easterly Jet) mainly during JAS season. The tropical easterly jet is

important for determining rainfall patterns in southern Asia and Africa. Rainfall at the surface has been found to be more to the north of the jet entrance in southern Asia region and south of the jet exit in the west Africa region (Hastenrath, 1985) as seen in figure 8.1 for the idealized cross circulation at the entrance and exit regions of the Tropical easterly jet.



Figure 8.1 Idealized cross circulation at the entrance and exit regions of the Tropical Easterly Jet (After Flohn, 1964)

- In the upper and middle levels, westerly winds over the Atlantic during MAM season are negatively correlated with Congo convection. This implies that subtropical zonal flow over the Atlantic is influenced by the Congo convection during MAM season.
- Easterly winds strengthen over South Atlantic during JAS season increases convection over Congo.

- Spatial pattern of vector wind at 200hPa for JAS season, using Congo convection as an index shows a strong relationship over South Africa at lag 0 and at lag2 (SON). As earlier seen in figure 4.5.
- Spatial pattern of vertical motion (omega) using Congo convection as an index show the prescence of a Walker circulation with an ascending arm over Indian ocean at 65°E, descending over East Africa, ascending over Congo and descending over Atlantic ocean (figure 8.2)



Fig. 8.2. Schematic diagram showing the vertical motion in an E-W direction during JAS season, depicting the prescence of an equatorial Walker circulation.

A spatial correlation analysis was worked out between Congo convection and rainfall Covering the equatorial zone from 40°W to 90°E for MAM season. The results for sig correlations are shown in figure 8.3. Areas which are positively correlated with Congo convec areas of ascending arm of the Hadley cell and negative for the descending arm as earlier seen i 8.2.



Figure 8.3 Correlation between Congo convection and rainfall for MAM season.

8.4 Summary of Chapter six

Congo convection as the driver of the African monsoon was determined by relating the respective monsoon winds with the Congo convection index.

Therefore the key associations of the Congo convection and monsoons are:

- The composite analysis for vertical motion at 500 hPa using (wet-dry) years index for Congo convection reveals a weak Walker circulation operating in the equatorial belt with an ascending arm over Congo and descending over east Africa and west Atlantic Ocean during JAS season.
- During JAS season there is a strong negative correlation <-0.4 at upper levels over east Africa with Congo convection. This scenario explains the subsidence over east Africa in this period.
- The SST's over Indian and Atlantic Oceans have a role to play in connection with convection in the continent. This is illustrated by a correlation <-0.3 between Congo convection and SST over the western coast during JAS season. The warm tropical Oceans help the African monsoon by its lateral coupling with the oceanic convection which is the driving force. Expansion of the monsoon area is possible with the warming of the Gulf of Guinea in JAS while the Indian Ocean cooling does not play much of a role due to subsidence there.</p>

8.5 Summary of chapter seven

- In this chapter models were developed to forecast JAS seasonal rainfall over Africa. The best model was obtained by using multiple linear regression analysis between a combination of Congo OLR (an index of Congo convection) and zonal wind at 700hPa over west Africa in the preceding season with Sahel rainfall.
- Models were also developed to forecast DJF rainfall. The best model is the combination of Congo OLR (an index of Congo convection) and NINO3 SST with DJF rainfall over West South Africa.
- The results show that Congo convection has a significant influence to the rainfall pattern in the subregion. The impact of rainfall on the economy and physical resource levels have been analyzed using examples from Zambia, and Tanzania. The results show that there is a significant relationship between GDP growth rate and local rainfall. The economies of the countries in the subregion are dependent on agriculture and therefore crop production is a critical element in human health and engagement in economic activities.

8.6 Conclusion and recommendations

The study has revealed that Congo convection plays a key role in influencing the weather over the region through supply of latent heat and moisture which is a driving force for most of the weather systems. The influence of Congo convection is only for a short period of 2 months compared to that of nearby Indian and Atlantic oceans, because of the relative small size and terrestrial nature of the Congo basin. The main findings were strong relationship between Congo convection and the following parameters.

- Zonal winds over Sahel during MAM and JAS seasons, extending from 60°W through 40°E and from surface to 500hPa with a peak at 600hPa while at 200hPa over South Africa during JAS season, Congo convection was leading the zonal wind.
- Congo convection leads QBO, suggesting that the convection is one of the sources of energy for QBO.
- Monsoon winds over eastern and western coasts of tropical Africa have a role to play in influencing convection over Congo.

During a wet scenario JAS season over Congo, the Walker cell has an ascending arm over the Congo basin, which is one of the ways in which latent heat and moisture is transported to upper atmosphere and the transported to other parts of the region.

Recommendations:

- Congo convection needs to be studied at shorter time scales i.e 5,10 days, in order to capture small duration waves passing through the Congo area e.g. Madden Julian (20-70 day) oscillations.
- More gauge rainfall data over Congo is needed for a thorough analysis of Congo convection. Radar installation could be of assistance, and satellite calibrations can be done.
- Relationship with tropical Atlantic Ocean variability need to be modeled numerically to establish cause and effect.
- Numerical simulations of the African monsoon with and without the Congo convection can be done to better quantify the coupling mechanisms.

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