INTER-HEMISPHERIC COMPARISON OF THE DYNAMICS OF RAIN-PRODUCING SYSTEMS IN TROPICAL AFRICA: A STUDY OF CLIMATE CHANGE WITHIN THE KALAHARI AND SAHELIAN TRANSECTS

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ABSTRACT

It is well documented that since the late 60's different parts of tropical Africa have experienced devastating droughts. The attendant inter-annual variability of rainfall and the shifts in the dynamics of the major rain-producing systems have also been the subject of much research work. This variability is closely linked with other global climatic conditions like the *El-Niño* (ENSO) phenomenon. The mechanisms for this inter-annual variability are discussed in relation to the modulating effects of continental rain-belt mode, large-scale atmospheric circulation and sea-surface temperature(SST) patterns. Observations show that above-normal (below-normal) Kalahari rainfall is usually accompanied by the southward (northward) displacement in the rain-belt mean axis, and there is a concurrent increase (decrease) in the total rainfall (Shinoda and Kawamura, 1994). Also, above-normal (below-normal) Kalahari rainfall is accompanied by dominant negative (positive) anomalies of 700 hPa heights over southern Africa. The correlation between tropical Africa rainfall patterns and global 700 hPa heights is therefore investigated with a two-layer model of the atmosphere. Results show that the most unstable perturbations occur when the interface between tropospheric air masses in tropical Africa is at 700 hPa whilst the locations where tropical Africa monsoon winds attain this critical precipitating depth of 700 hPa is determined by global SST anomalies. Another interesting solution was obtained for a wave-like disturbance which has a phase speed of 6.0 ms^{-1} in the East-West direction, a wavelength of 2000 km, a period of 3.49 days and growth rate of 3.6 per hour, when the surface of discontinuity between the North East monsoon and the South East trade winds, in southern Africa, is at 500 hPa (Mphale, 1999). It is shown that the axis of this wave is greatly influenced by the Indian Ocean SST. A look at the ECMWF analyses for MSL and vertical velocity at 400 hPa during a period of convective activities over Botswana (15-21 February 1995) confirmed the existence of this wave pattern. In Sahelian Africa, the same dynamic pattern is observed. This is shown to influence the southward shift in the axis of squally activities during dry ENSO events, thereby depriving the northern part of this sub-region of its main rain-producing mechanism. Implications of observed variabilities on water resources, agriculture, energy, health-related issues and the tourism industry are discussed.

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1. INTRODUCTION

More than three-quarters of the total annual rainfall in Sahelian Africa are attributable to squall lines (Eldridge, 1957; Omotosho, 1985, 1990). Adedoyin(1989b, 1989c) has shown that the process of initiation of these tropical disturbances is linked with the instability of waves generated along the surface of discontinuity between the two tropospheric air masses (i.e. the moist south-westerlies and the dry north-easterlies) in the sub-region. These squall-inducing vertical transverse waves are likely initiated by the passage of the trough of the dominant horizontal transverse wave in tropical north Africa namely, the African Easterly Waves(AEW). It may therefore seem that the more the number of AEW in any year, the more the number of squally activities and the better the rainfall regime in Sahelian Africa.

In pursuance of this hypothesis, Reed(1988), Druyan(1989) and Landsea and Gray(1992) have suggested that AEW are less numerous in Sahelian dry years but Pasch and Avila(1994) have shown that the number of waves per year is relatively constant (around 60) no matter if the Sahel is wet or dry. Therefore, the reduction in the number of squall lines in the Sahel in dry years, as found by Adedoyin(1989a), cannot be conclusively ascribed to a reduction in the number of AEW.

However, one synoptic feature which seems to distinguish Sahelian dry years from the wet is the strength of the African Easterly Jet(AEJ). AEJ is stronger in dry years (Newell and Kidson, 1984; Janicot, 1992). There is therefore a need to investigate whether or not there is any relationship between enhanced horizontal shear (caused by stronger AEJ) in the lower troposphere of West Africa and the evolution of wave-like perturbations along the surface of discontinuity between the two tropospheric air masses in the sub-region since, the amplification of these perturbations has been shown to be fundamental to the development of squall lines (Adedoyin, 1989b, 1989c). This paper examines the effects of an increase in the strength of the AEJ on amplifying waves along the surface of discontinuity between the moist south-westerlies(SW) and the dry north-easterlies(NE) in tropical north Africa. The strength of the AEJ is then linked with global sea-surface temperature(SST) anomalies and the persistence of drought in the sub-region since the late 60's.

To appreciate changes in tropical south Africa rainfall pattern, in relation to global climate variability, knowledge of the air masses that bring moisture to different parts of the tropical Africa sub-continent is necessary. Adedoyin(1989c) has described the scenario for tropical north Africa but the case for tropical south Africa, especially Botswana, should be mentioned.

1.1 The Northwest Winds

Changes in temperature due to differential heating of land and sea during the summer months in the southern hemisphere lead to the development of a low-pressure area in the western part of Angola, the Angola low. Due to this development, southeast trade winds, originating from South Atlantic Ocean, are drawn towards the clockwise circulation of Angola’s semi-permanent low-pressure center into the sub-continent. This unstable, humid, summer monsoon air mass traverses through the Democratic Republic of Congo into Zambia as the northwest winds. It shares a boundary with the southeast trade winds, and its incursion inland brings limited amount of rain to the northwestern part of Botswana.

1.2 The Southeast Trade Winds

The southeast trade winds originate from the eastern flanks of the subtropical high and flow west towards the equator. The low-pressure system over southern Africa during the summer months draws these winds from the Indian Ocean into the landmass. Over Madagascar, these winds pass over the steep slopes in the eastern part of the island and lose a large percentage of their moisture. As the winds are drawn inland, they pass over the warm Mozambique Ocean current drawing both warmth and moisture. The branches of these winds that continue in the easterly direction prevail over southern Zimbabwe. These winds meet the northeast monsoons at a strong zone of convergence, which is part of the Inter-tropical Convergence Zone (ITCZ) observed over tropical Africa. The incursion of the ITCZ into Botswana is important in respect of rainfall over the northeastern part of Botswana.

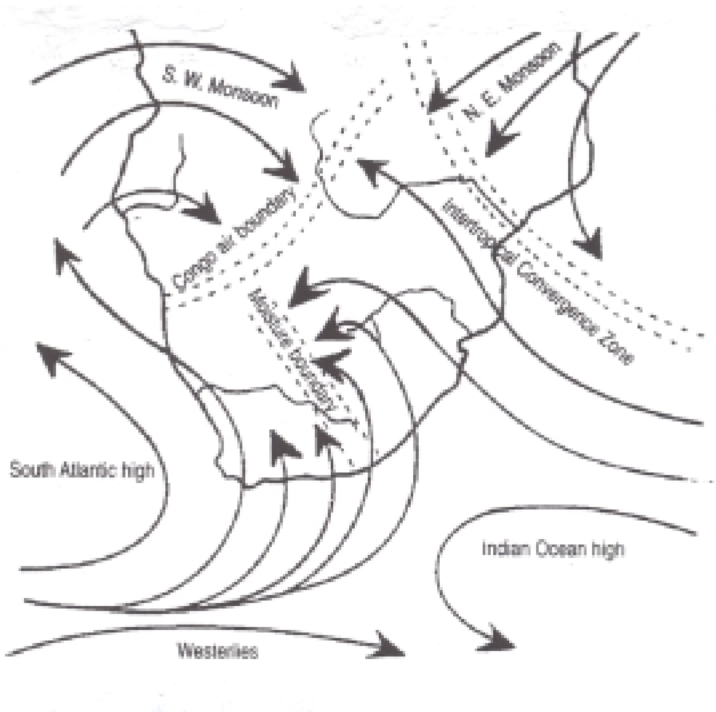

Fig. 1 Prevailing air masses over southern Africa (Tyson and Preston-Whyte, 2000)

1.3 The Northeast Monsoons

The Tibetan plateau blocks the westerly jet stream in the lower stratosphere, which is placed north of the Himalayas during the Southern Hemisphere summer season. This descending air mass, combined with loss of radiation from snow-covered peaks of the plateau, lead to the development of a strong anticyclone over central Asia. This anticyclone is the genesis of an outward-blowing northeast winds that cross the equator towards Africa. On crossing the equator, these winds veer anticlockwisely due to Coriolis effect to meet the northbound branches of the southeast trade winds at the ITCZ.

The Northwest winds, the Southeast trade winds and the Northeast monsoons all bring rain to different parts of Botswana. The overland depth of these winds determines various types of rain-producing mechanisms. The dynamics of these mechanisms respond to changes in the global climate.

2. BASIC AND FREQUENCY EQUATIONS

The horizontal and vertical momentum equations, including viscosity terms, can be written in Cartesian co-ordinates as:

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}.\Delta)\vec{u} + \vec{f}k \wedge \vec{u} + \frac{\Delta P}{\rho} + g = \nu\, \Delta^2 \vec{u} \qquad (1)$$

where all notations and symbols have their usual meaning, but for the purpose of clarity are spelt out in Appendix A. The first law of thermodynamics for moist adiabatic motion can be expressed as:

$$\frac{D}{Dt}\left(\frac{Lr}{C_p} + \theta \right) = 0 \qquad (2)$$

where

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial X} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial Z}$$

while the equation of continuity of mass and conservation of water substances are:

$$\frac{D\rho}{Dt} + \rho\Delta\vec{u} = 0 \qquad (3)$$

and

$$\frac{D}{Dt}(r + q) = 0 \qquad (4)$$

respectively. Potential temperature is defined as:

$$\theta = T\left(\frac{P_0}{P} \right)^{\kappa} \qquad (5)$$

The viscosity terms can be neglected in the momentum equations because the scale of motion envisaged in this study exceeds molecular dimensions. As a further approximation, the hydrostatic relation may be assumed for all atmospheric phenomena with a horizontal extent larger than the vertical extent - a situation which is applicable to squally thunderstorms.

Atmospheric disturbances can be assumed to be wave-like perturbations superimposed on the basic state of the atmosphere. If these perturbations are expressed in the form

$$u' = u(p)\, e^{i(\sigma_0 t + \alpha x + \beta y)}$$
$$v' = v(p)\, e^{i(\sigma_0 t + \alpha x + \beta y)}$$

etc. and Eqs.(1)-(5) transformed into their equivalents in pressure co-ordinates with the Coriolis term neglected because it is of a second order of smallness for the area of study

If μ_1, μ_2 and μ_3 are tracer elements attached to the horizontal advection, Coriolis and latent heat terms respectively, we obtain

$$\frac{\partial^2 \omega}{\partial p^2} + \frac{g\Gamma}{p_s^2}\left(\frac{\alpha^2+\beta^2}{\sigma^2}\right)\left(1-\mu_1 . \frac{\alpha u_s}{\sigma}\right)\omega = -\mu_2 \frac{f}{\sigma}\frac{\partial}{\partial p}(\beta u_s) \qquad (6)$$

where the atmospheric static stability is expressed in units of length as:

$$\Gamma = \frac{R^2 T_s}{g^2}\left[\frac{g}{C_p}\left(1-\frac{\mu_3 L P_s \partial r}{R\theta_s \partial p}\right)-\gamma\right]$$

and R is the gas constant

2.1 Solution to the Frequency Equation

The solution to Eq.(6) is of the form

$$\omega = A(P)\, P^{\frac{1}{2}+\lambda} + B(P)\, P^{\frac{1}{2}-\lambda} - \frac{4CP^2}{9-4\lambda^2} \qquad (7)$$

where A and B are constants and

$$\lambda = \left\{\left(\frac{1}{4}-\frac{g\Gamma(\alpha^2+\beta^2)}{\sigma^2}\right)\left(1-\mu_1 . \frac{\alpha u_s}{\sigma}\right)\right\}^{\frac{1}{2}}$$

Applying some boundary conditions(Adedoyin, 1997) to Eq.(6) results in:

$$\left\{\left[Q_1\left(\frac{1}{2}+\lambda_1\right)-H_B\right]+\left[Q_1\left(\frac{1}{2}-\lambda_1\right)-H_B\right].R_1\right\}.\frac{P_B^{\lambda_1}}{\sigma_1}.A_1$$
$$+\left\{\left[Q_2\left(\frac{1}{2}-\lambda_2\right)-H_B\right].R_2-\left[Q_2\left(\frac{1}{2}+\lambda_2\right)-H_B\right]\right\}.\frac{P_B^{\lambda_2}}{\sigma_2}.A_2 =$$
$$\left\{\left[Q_1\left(\frac{1}{2}-\lambda_1\right)-H_B\right].R_3+\left[2Q_1-H_B\right]\right\}.\frac{P_B^{\frac{1}{2}}}{\sigma_1}.N_1$$
$$+\left\{\left[Q_2\left(\frac{1}{2}-\lambda_2\right)-H_B\right].R_4-\left[2Q_2-H_B\right]\right\}.\frac{P_B^{\frac{1}{2}}}{\sigma_2}.N_2 \qquad (8)$$

$$\{1+R_1\}.\frac{P_B}{\sigma_1}^{\lambda_1}.A_1-\{1-R_2\}.\frac{P_B}{\sigma_2}^{\lambda_2}.A_2=$$

$$\{1+R_3\}.\frac{P_B^{\frac{1}{2}}}{\sigma_1}.N_1-\{1-R_4\}.\frac{P_B^{\frac{1}{2}}}{\sigma_2}.N_2 \qquad (9)$$

where subscripts *'O', 'B'* and *'T'* respectively indicate values at the base, boundary and top of the two-layer model. Subscripts *'1'* and *'2'* indicate values within the model's lower(i.e. SW) and upper(i.e. NE) air masses, respectively, in the case of tropical north Africa.

Eqs. (8) and (9) are simultaneous in A_1, A_2 and they can be written in matrix form. The method of solution of the matrix equation is contained in Appendix B. If Appendix B is applied to Eqs. (8) and (9) the result is:

$$\sigma_0^2\left\{\left[2\lambda_1\left(\frac{1+R_1}{1-R_1}\right)+1+D_1\right]-\left[2\lambda_2\left(\frac{1+R_2}{1-R_2}\right)+1+D_2\right]\right\}$$

$$+\sigma_0\left\{2\alpha u_1\left[2\lambda_1\left(\frac{1+R_1}{1-R_1}\right)+1+D_1\right]-2\alpha u_2\left[2\lambda_2\left(\frac{1+R_2}{1-R_2}\right)+1+D_2\right]\right\}$$

$$+\left\{\alpha^2 u_1^2\left[2\lambda_1\left(\frac{1+R_1}{1-R_1}\right)+1+D_1\right]-\alpha^2 u_2^2\left[2\lambda_2\left(\frac{1+R_2}{1-R_2}\right)+1+D_2\right]\right\}=0 \qquad (10)$$

where

$$D_1=N_2\sigma_2(1-R_4)[\lambda_1(1-R_1)+\frac{1}{2}(1+R_1)]$$

$$D_2=N_2\sigma_2(1+R_1)(\frac{R_4}{2}-2)-N_2\sigma_2\lambda_2R_4(1+R_1)$$

$$-N_1\sigma_1\lambda_1(1-R_1+2R_3)+\frac{3}{2}N_1\sigma_1(1+R_1)$$

Results show that some modes of the wave-like disturbances generated along the surface of discontinuity between the air masses propagate and amplify with time. In the case of West and Central Africa, this instability is found to be most-pronounced when the surface of discontinuity between the South-westerlies and the North-easterlies is at 700 hpa level. Further, it is shown that in Sahelian dry years, the zone of these unstable waves shifts slightly southwards. This shift causes a deficit in rainfall in West African isohyet bands north of latitude 12^0. The persistence of this deficit is linked with the continuous warming, in July, August and September of the 18-year period 1969-1986, of the three oceans (Indian, Pacific and South Atlantic) whose sea-surface temperature(SST) anomalies influence rainfall in tropical north Africa. It is shown that anytime these oceans warm up anomalously, the strength of the AEJ is enhanced leading to the climate-change process of: SST anomaly, increased AEJ strength, southward shift of the zone of squall-inducing waves and consequent reduction in total annual rainfall north of latitude 12^0 in tropical North Africa. In the case of East and Southern Africa, a solution was obtained for a wave-like disturbance which has a phase speed of 6.0 ms^{-1} in the East-West direction, a wavelength of 2000 km, a period of 3.49 hours and growth rate of 3.6 per hour, when the surface of discontinuity between the North East monsson and the South East Trade winds is at 500 hpa. It is shown that the axis of this wave is greatly influenced by the Indian ocean SST. A look at the ECMWF analyses for MSL and vertical velocity at 400 hpa during a period of active convective activities over Botswana (15-21 February, 1995) confirmed the existence of this wave pattern. These results have applications, and implications, in the health and tourism sectors of some countries in Africa. Although the scheme developed has been applied to atmospheric dynamics, it can be used to study any wavelike disturbance at the interface between any two fluids of different densities.

3. CLIMATE VARIABILITY IN BOTSWANA

Area mean of annual maximum temperature over southern Africa indicates that 1920 was the warmest period during the twentieth century while the 60s and 70s were cooler. Experience in the recent past indicates that the region has been warming steadily since the late 60s. This steady rise in temperature has been attributed to the rising level of greenhouse gases in the atmosphere and ultimately, this is expected to lead to climate change.

Apart from the chlorofluorocarbons (CFCs), all other greenhouse gases occur naturally but the level of emission of most of them is directly related to human activities. These activities are global in nature and the effects are not limited by political boundaries. Therefore, a country like Botswana that may not necessarily contribute to the increase in the level of greenhouse gases in the atmosphere will suffer the attendant adverse effects in terms climate change. For instance, it is projected that global average temperature will rise by about 2^0C at the end of this century if current emission trends of greenhouse gases continue.

Although all areas of the globe are expected to warm up, there will be regional differences. The quantitative changes within the tropics will be more difficult to predict because of lack of empirical evidence based on realistic simulations from models. This notwithstanding, there could be glimpses to indicate possible trends. For instance, has climate change already begun in Botswana?

3.1 Temperature trends in Botswana

The mean annual maximum temperatures at four different locations in Botswana over a period of approximately 30 years are shown in Fig. 2. These locations are Francistown (21.22^0S 27.50^0E), Maun (19.98^0S 23.42^0E), Tshane (26.02^0S 21.88^0E) and Gaborone (24.67^0S 25.92^0E), and they have been chosen to depict the trends at the northeastern, northwestern, southwestern and southeastern parts of the country respectively. From these figures, it is obvious that there is a trend towards an increase in maximum temperature in Botswana ranging from 0.4^0C in Gaborone to about 1.3^0C in Francistown. This trend conforms with the observations all over the globe and perhaps indicate that there is evidence of a progressive change in climate in Botswana.

3.2 Rainfall trends in Botswana

The rainfall trends at the four locations: Francistown (21.22^0S 27.50^0E), Maun (19.98^0S 23.42^0E), Tshane (26.02^0S 21.88^0E) and Gaborone (24.67^0S 25.92^0E), are shown in Fig. 3. The plotted trends on these figures indicate a tendency towards a decline in total annual rainfall at all locations with Maun showing the greatest decline rate. In the case of Maun, the likely explanation is that anomalies in South Atlantic sea-surface temperatures might have affected the depth of the Northwest Winds over the station thereby reducing convective activities associated with rainfall. Further, concentration of aerosols in the atmosphere increases percentage of the sun's energy scattered back into space. This has implication for the intensity of the long-wave infrared radiation that the Earth re-emits and, consequently, the level of convective activities.

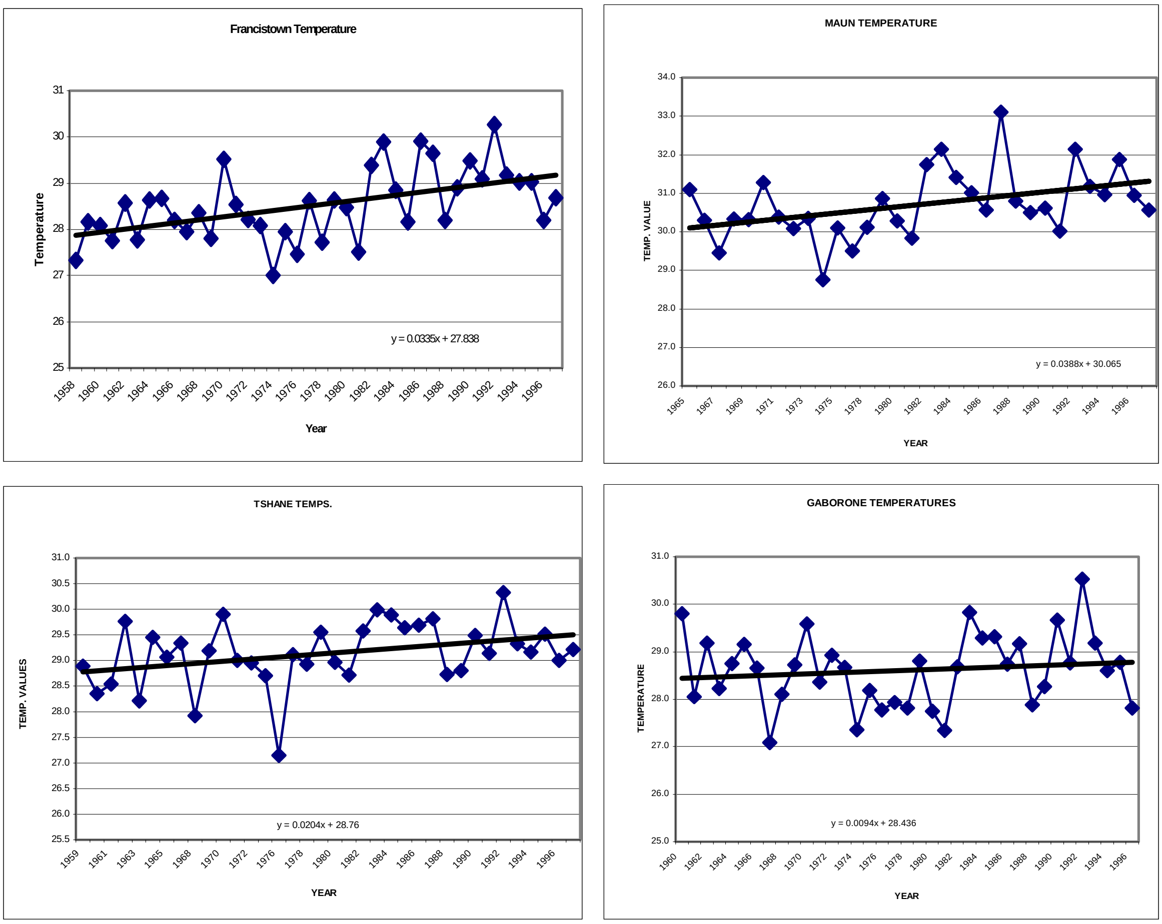

Fig. 2 Trend of maximum temperature over a 30-year period in Francistown (21.22^{0}S 27.50^{0}E), Maun (19.98^{0}S 23.42^{0}E), Tshane (26.02^{0}S 21.88^{0}E) and Gaborone (24.67^{0}S 25.92^{0}E) (Data from Botswana Met Office)

4. IMPACTS OF CLIMATE CHANGE IN BOTSWANA

The norm in scientific circles is to convert the greenhouse effect of gases that absorb infrared long-wave radiations, emitted by the sun-heated Earth, to their carbon dioxide equivalent. This way, climate change can be quantified in terms of percentage increases in carbon dioxide. Given this norm, it is easy to quantify how the effect of doubling the amount of carbon dioxide in the atmosphere will impact on various sectors of Botswana economy including water resources, agriculture, health-related issues and energy sources.

4.1 Effects of climate change on water resources in Botswana

A change in the global climate towards a hotter environment will lead to more precipitation and also, more evaporation. Precipitation will increase in some regions of the world and reduce in others. Semi-arid countries of the world, like Botswana, will be sensitive to reduced rainfall because changes on the surface with respect to run-off will influence the recharging process of groundwater supplies.

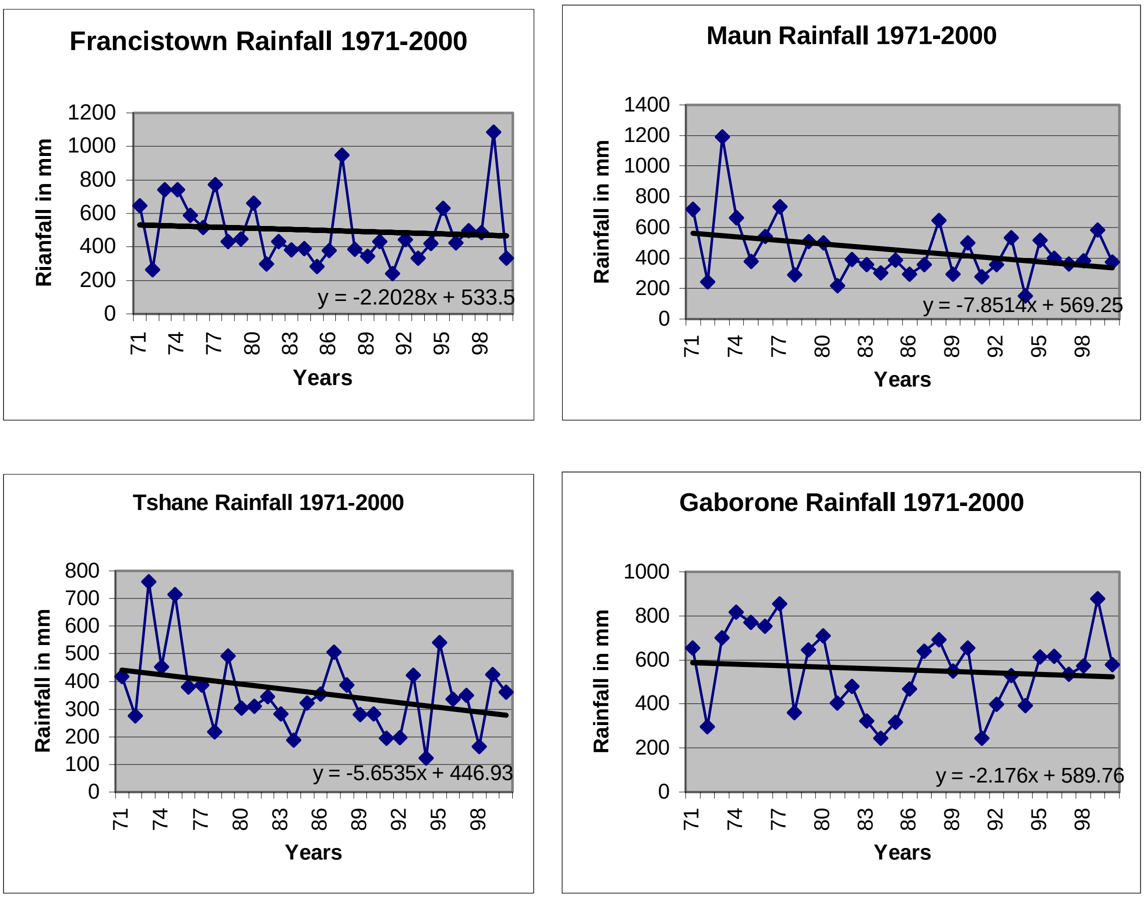

Fig. 3 Trend of rainfall over a 30-year period in Francistown (21.22^{0}S 27.50^{0}E), Maun (19.98^{0}S 23.42^{0}E), Tshane (26.02^{0}S 21.88^{0}E) and Gaborone (24.67^{0}S 25.92^{0}E) (Data from Botswana Met Office)

Zhou and Masundire (1998) have studied the possible effects of doubling atmospheric carbon dioxide on five major water catchments in Botswana namely, Notwane-Metsimotlhaba, Mahalapye, Lotsane, Motloutse and Shashe Rivers, and predicted a total catchments shortfall of about 200% by the year 2020. This outlook is rather grim and if the trend of emission of greenhouse gases is not reversed, there will be need for adaptation measures like inter-basin transfer of water (e.g. from Okavango and Zambezi) and water recycling.

The model of Zhou and Masundire (1998) based run-off estimates (i.e. supply) on the Pitman's Water Resources Model (WRM90) for two scenarios: no climate change (i.e. stabilized of CO_2 concentration over the globe) and doubling of CO_2 concentration. Demand was based on all water uses under a demographically normal growth rate.

4.2 Effects of climate change on agriculture in Botswana

The impact of climate change on crop yields will vary. Some agricultural regions of the world will benefit while others will be threatened. Higher temperatures may influence production patterns because agricultural zones will shift polewards. The effect of climate change on agriculture in Botswana is two-fold: livestock and crops. While it is envisaged that some crops will yield more if carbon dioxide concentration doubles in the atmosphere, this boost will not affect tropical crops like sorghum and maize, which are planted in Botswana. The consequent higher grain prices may then lead to costlier livestock production.

4.2.1 Livestock

The livestock sector accounts for about half of the agricultural GDP of Botswana. This sector depends on the grazing of natural rangeland and is therefore sensitive to climate variability. Future increase in temperature due to greenhouse gases effects and decrease in rainfall would result in more frequent and extended droughts, less moisture in the soil and less vegetation cover for grazing. Dehydration also affects mortality rates in stocks. The cumulative impact of increased temperature is therefore devastating for this sector of the economy. Adaptation measures should include diversification of breeds, creation of grazing reserves etc. (Setshwaelo, 2000).

4.2.2 Crops

Crop agriculture is not well developed in Botswana because of poor soils and a harsh climate. The major crops are cereals like sorghum and maize that require a relatively short time to mature. Even within this short period, if there is shortfall in water supply, the crops will be stressed and crop yields will be low. A drier, hotter future will therefore lower crop yields, which could inform an adaptive method of minimum tillage method to conserve soil and water (Chanda *et al*., 1999).

Chanda *et al*.(1999) used a dynamic model, CERES (Crop Estimation Through Resource And Environment System), to simulate crop growth and development under different climate change scenarios and found very little overall trend in yield per hectare of major crops like sorghum, maize and millet in Botswana.

Totolo(2001) used Global Circulation Model(GCM) results to show that mean agricultural production may be reduced in parts of Botswana with low water retention capacity e.g. Ngamiland West. This situation will adversely affect crops, like maize, which are more sensitive to moisture deficiency than, say, sorghum. As an example, in 1993 (a dry year) traditional farmers planted 66,562 ha of sorghum which yielded 10,797 tons of grain while, in the same year, 22,185 ha of maize yielded 2,976 tons of grain.

4.3 Effects of climate change on health-related issues in Botswana

Increased environmental temperature has implication on health-related issues. While stress in water resources will increase the incidence of infectious diseases like cholera, warmer climate will enhance the spread of vectors of diseases like malaria. In the case of Botswana, a drier environment will lead to a reduction in the incidence of malaria (even if the environment gets warmer) because the transmission of the disease depends on temperature and rainfall. A hotter, wetter environment is potentially hazardous because the disease may then spread beyond its present confines in the northern part of the country. The other potential hazard for increase in the occurrence of malaria is not related to climate: some strains of the parasite are getting resistant to drugs used for prophylaxis and treatment.

In a specific study on vulnerability and adaptation of the health sector to effects of climate change in Botswana, Nzinge and Bagwasi(2000) postulated that a southward shift in the endemic malaria region of the country will be consistent with predictions of climate change models. From their study, it is envisaged that the population in malaria-prone zones of Botswana will double by the year 2021 and this may make effective large-scale control measures more difficult. Nzinge and Bagwasi(2000) also think that climate change scenarios which lead to more use of contaminated water will likely increase the prevalence of infant diarrhoea.

Other diseases that could be related to climate change include dengue fever, schistosomiasis and asthma. Up to the present however, the relationship has not been quantified for the country.

4.4 Effects of climate change on energy sources in Botswana

Production and use of energy are the leading sources of greenhouse gas emissions worldwide. This is particularly so in Botswana where about 70% of the energy supply is from fuel wood. Depletion of this source without an accompanying programme for replenishment has profound implication for future energy supply in the country. The Morupule power station, which has an installed capacity of 132 MW, generates electricity from coal, which is another source of greenhouse gas emission. The energy sector in Botswana therefore seems very vulnerable to climate change scenarios

5. MECHANISM FOR INTER-ANNUAL VARIABILITY IN CLIMATE

Analyses by Adedoyin(1997) have shown that a mode of the unstable waves, generated along the surface of discontinuity between SW and NE in tropical north Africa, propagates and amplify with time when there is no horizontal shear in the environment and the boundary P_B between these air masses is between 830 mb and 700 mb. The introduction of horizontal shear, which is consistent with an increase in the strength of the AEJ in dry Sahelian years, caused the value of P_B, for amplifying waves, to shift from 830-700 mb to 700-650 mb.

Further analyses also showed that the zone of amplifying waves shifted from $830 \leq P_B \leq 700$ mb to $700 \leq P_B \leq 650$ mb with increasing horizontal shear (consistent with stronger AEJ's). Effectively, this is a southward shift because the depth of the southwesterlies increases southwards from the surface position of the Inter-tropical Discontinuity(ITD). In other words, zone C of Hamilton and Archbold(1945) (i.e. zone of squally activities), which is about 500 km south of the northernmost extent of the ITD position in July/August, shifts slightly southwards in dry Sahelian years.

Similar studies by Mphale(1999) with the aid of a two-layer model of the atmosphere confirmed the observation of Shinoda and Kawamura(1994) that above-normal (below-normal) Kalahari rainfall is usually accompanied by the southward (northward) displacement in the rain-belt mean axis, and there is a concurrent increase (decrease) in the total rainfall (Shinoda and Kawamura, 1994), and that above-normal (below-normal) Kalahari rainfall is accompanied by dominant negative (positive) anomalies of 700 hPa heights over southern Africa. The correlation between Kalahari rainfall and global 700 hPa height anomalies is investigated with the aid of a two-layer model of the atmosphere.

This result most likely explains the variations in squall activities associated with the displacement of the rain-belt axis within the Kalahari transect. A northward displacement of the rain-belt obviously implies less rainfall in the north-western corner of Botswana and the northern part of Namibia, along with the associated trauma of poor agricultural yields and increased mortality in livestock as well as wild animals.

6. CONCLUDING REMARKS

Investigations in this study reveal that the warming up of the Indian, Pacific and South Atlantic Oceans strengthens the AEJ. Stronger AEJ, on the other hand, leads to a southward shift of the zone of squally activities in tropical north Africa thereby resulting in rainfall deficits north of latitude 12^0. The change in climate, arising from reduced total rainfall amounts in the Sahel since the 60's, has been found to be attributable to the fact that the SST's of the three influencing oceans have persistently warmed up in July, August and September of the 18-year period 1969-1986. Other observed meteorological features like increased albedo, due to possible over-grazing by livestock, may therefore be effects, and probably not the cause, of the persistent drought in the Sahel. The amazing thing is that these three separate SST anomalies, each leading to rainfall deficits in the Sahel, have occurred simultaneously for about three decades without interruption. It is probably an attestation to the fact that there have been changes in the global climate in recent years.

The climate of Botswana is typically semiarid and therefore fragile as well as vulnerable to global climatic changes. While the country may not be a major contributor to some of the factors that cause climate change, it is difficult to insulate any part of the globe from the effects of anthropogenically-induced factors of climate change. For instance, Botswana is regarded as net sink for greenhouse gases but there is evidence that the temperature of the country is rising, just as in most other parts of the globe, while the total annual rainfall is declining. It is therefore imperative for all countries to embark on processes that mitigate against global warming in order improve the health, energy sources, agriculture and water resources for mankind; especially in a vulnerable environment like Botswana.

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Appendix A

Notations and Symbols

u	-	x component of velocity
v	-	y component of velocity
w	-	vertical velocity
p	-	pressure
ρ	-	air density
g	-	acceleration due to gravity
ν	-	coefficient of viscosity
f	-	Coriolis parameter
L	-	latent heat of vapourisation of water
H	-	scale height
r	-	condensed water vapour per unit mass of air
q	-	specific humidity
c_p	-	specific heat capacity at constant pressure
c_v	-	specific heat capacity at constant volume
θ	-	potential temperature
κ	-	$(c_p - c_v)/c_p$
T	-	temperature
z	-	vertical height
k	-	unit vector along the vertical
σ	-	angular frequency
α	-	wave number along x direction
β	-	wave number along y direction

Appendix B

Any two simultaneous equations in variables x and y can be expressed in matrix form as:

$$\begin{pmatrix} a_1 & b_1 \\ a_2 & b_2 \end{pmatrix} . \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} \qquad B1$$

from which a matrix A can be defined as:

$$A = \begin{pmatrix} a_1 & b_1 \\ a_2 & b_2 \end{pmatrix}$$

and from which the following augmented matrix can be deduced:

$$A^* = \begin{pmatrix} a_1 & b_1 & | & c_1 \\ a_2 & b_2 & | & c_2 \end{pmatrix} \qquad B2$$

A solution exists for variables x and y $\Leftrightarrow$ Rank A = Rank A^*.

Matrix A^* can be transformed to an equivalent matrix as:

$$A^* = \begin{pmatrix} a_1 & b_1 & | & c_1 \\ 0 & p & | & q \end{pmatrix} \qquad B3$$

and a solution exists for x and y in B1 $\Leftrightarrow$ in B3
(a) $p \neq 0$ if $q \neq 0$;
(b) $p \neq 0$ if $q = 0$;
(c) $p = 0$ if $q = 0$.

Eqs. (14) and (15) are in the form of B1 if $x = A_1$ and $y = A_2$. The equivalent expressions for p and q (in B3) are $p = b_2 - (b_1.a_2)/a_1$ and $q = c_2 - (a_2.c_1)/a_1$. Applying condition (c) for the existence of a solution to B1, $q = 0 \Rightarrow a_1 .c_2 = a_2 .c_1$ while $p = 0 \Rightarrow a_1 .b_2 = a_2 .b_1$. The case $p = 0$ is equivalent to taking $\mu_1 = 0$ in Eqs. (14) and (15) and this has been solved by Adedoyin(1989c).