Rainfall of the Sudan: Characteristics and Prediction

Tarig El Gamri[1] Amir B. Saeed[2] AbdallaK. Abdalla[3]

Abstract:
The paper highlights challenges facing the water sector at the global and national levels. The impacts of rainfall variability on the environment and socioeconomic conditions of the Sudan were discussed. Taking into consideration factors affecting rainfall of the country like the position of the Inter-Tropical Discontinuity Zone (ITDZ), the subtropical anticyclones and climate change. Recent studies showed that the areal annual averaged rainfall values of the country decreased markedly since early sixties. It varies from almost nil in the North to about 1500 mm at the extreme Southwest. The rain-producing clouds in tropical areas including Sudan belong to the vertically-developing group. The months of July –August-September were found to constitute the general rainy season of the Sudan. The paper also reviews rainfall prediction studies that use both the El Nino Southern Oscillation (ENSO) event and global Sea Surface Temperatures (SSTs) as predictors. However, more emphasis has been given on the ENSO event because of its global popularity as a rainfall-predictor. The paper concluded that Sudan's rainfall can reasonably be predicted and more accuracy can be obtained with further studies.

1.0 Introduction:

Challenges faced by more and more countries in their struggle for economic and social development are being increasingly related to water (GWP, 2000). Water shortages, quality deterioration and flood impacts are among the problems which require greater attention and action. It is envisaged that the problem of water shortage will be aggravated in many parts of the world in the very near future. This is mainly attributed to increased economic activity, improved standard of living and expansion in the agricultural sector to satisfy the growing human demands. It is

[1] Head, Water Resources Dept., Desertification Research Inst., The National Centre for Research
[2] Dept of Agricultural Engineering, Faculty of Agriculture, University of Khartoum
[3] Sudan Meteorological Authority

worth mentioning that irrigated agriculture is the main user of water, then industry and municipalities.

Sudan is a vast country with an area of about 2.5 million km^2 and hosts an estimated population of about 40 million people. About two- thirds of Sudan lies in the dry and semidry region, which extends to about 96% of the total geographical area in North Africa and the Near East and 87% in the Middle East (Saeed and El Gamri, 2000). The region is characterized by low, unpredictable and highly variable rainfall. Temperature and evaporation rates are high and droughts are more the rule rather than the exception. In the dry and semidry regions the variability of the rainfall can be extremely high to the extent that the daily maximum may reach the annual average. Consequently the two extreme phenomena of drought and flood may occur with drastic influences on man, property and environment.

Most of the disasters in Africa are climate–driven. Drought (slow onset) and floods (quick onset) are part of the climate system and therefore unavoidable (Mutua, 2004). According to NSF, (2003) unanticipated severe drought will be a feature of climate in the future as it has been in the past.

In Sudan the 1984 drought resulted in crop failure, spread of water-borne diseases as a result of people gathering around water sources and demographic changes due to internal migration to urban centres (Osman and Shamseldin, 2002). Results of that environmental disaster included the death of 55000 people and the weakening of the socioeconomic capabilities of the nomadic tribes. On the other hand, the floods and heavy rains of 1988 affected about one million people, destroyed crops, increased malaria infections and other water-borne diseases. Such phenomena also represent a serious challenge to developed countries. For instance, the short 1988 summer drought in USA was reported to have costed $40 billion (NSF, 2003). Such adverse impacts could have been reduced through developing reliable seasonal rainfall forecasts (Osman and Shamseldin, 2002; Cobon *et al.*, 2003a; Mutua, 2004).

2.0 Rainfall of the Sudan:

Rainfall plays a central role in the environment and the socioeconomic conditions of the Sudan. For instance remote sensing studies showed that the vegetative cover of the country, measured as Normalized Difference Vegetation Index (NDVI), expands and contracts dramatically following the characteristics of the rainy season (Hellden, 1991; Giannini *et al.*, 2003). Rain fed agriculture, which is considered as one of the vital sectors in the Sudanese economy, is directly affected by the amount and distribution of rainfall (MOIWR, 1999; Adam, 2000). During drought years the physical and sexual maturities of farm animals are severely retarded because less feed stuffs are available. During wet years the national herd will tend to expand and consequently animal losses and overgrazing during dry years will increase. Hence, flexible management practices and marketing policies are to be used to regulate the herd size (El Gamri *et al*., 2003).

Precipitation forms the third stage in the hydrological cycle preceded by evaporation and condensation. Uplifting of air current which is caused by orographic, frontal or thermal effects is a prerequisite for condensation (Ward and Robinson, 1990). As will be illustrated later potentialities of orographic uplifting are very limited in the Sudan. On the other hand, the potentialities of frontal developments are practically non-existent. As a consequence of its tropical continental location, the country experiences fairly high temperatures throughout the year, this means that thermal uplifting is of high potentialities in the Sudan (El Tom, 1975).

2.1 Factors influencing rainfall of the Sudan:

2.1.1 The position of the Inter-Tropical Discontinuity Zone (ITDZ):

The ITDZ is defined as a transitional belt of low pressure that separates the dry northeasterly winds from the moist southwesterly winds. As a result of density-contrast the northeasterly winds converge (ride) above the southwesterly winds i.e. the vertical distance between the ground surface and the ITDZ increases gradually southwards (El Tom, 1975). Annually the ITDZ enters the southern borders of the country in early March and reaches its ultimate northern position (Lat. 20º N) in August. During September the ITDZ starts its return movement and goes outside the Sudanese territories in either the end of November or early December (MOIWR, 1999).

The rain belt is usually about 300 - 600 km south of the ITDZ (El Tom, 1975). There is generally a drop outside these limits to the north as well as to the south i.e. precipitation does not increase southward during the whole season as used to be believed for a long time. According to El Tom, (1975) this can be attributed to the following three main reasons:

- The point of maximum precipitation coincides with the core of the Tropical Easterly Jet Stream (TEJS) i.e. 300-600 km south the ITDZ.

- Invasion of anticyclones (high pressure systems) from the Southern Hemisphere. It is worth mentioning that anticyclones are characterized by stability or vertical subsidence (downward motion) and horizontal divergence and hence they reduce rainfall potentialities.
- During the peak of the rainy season temperatures over Southern Sudan are relatively lower due to the presence of extensive forests and swamps and hence the convective potential is reduced.

The retreat of the ITDZ is sometimes characterized by rains in areas adjacent to its north position resulting from residual moisture.

2.1.2 The four sub-tropical high pressure systems:

These include the Mascarene, the St. Helena, the Azores and the Arabian high pressure systems. According to Abdalla, (2002) Mascarene and St. Helena are identified as energy generators and they play an important role in the development of the monsoon season. They are known to be the origin of moisture that feeds the Ethiopian Plateau, Equatorial Plateau and the Congo Basin. Meanwhile the Equatorial zone is a reservoir of water vapour that extends deeply in the lower atmosphere. The penetration of moisture from this zone through the monsoon winds to the North is controlled by the thermal influences generated by the apparent movement of the Sun to the tropic of Cancer.

The expansion and shrinkage of the Indian Monsoon low in eastern Africa (including Sudan) depends on the pressure pattern shaped by the two high pressure systems over Europe and Northwest Africa (Okoola, 1999).

2.1.3 The inter-hemispherical monsoonal wind systems:

The main causes of rainfall in Sudan are attributed to the low southwesterly monsoons (at the lower part of the Troposphere of about 1.5 km) flowing from the Atlantic Ocean and the relatively high southeasterly monsoons (at the middle part of the Troposphere of about 1.5 - 5 km) flowing from the Indian Ocean. The extent of their inland coverage determines the annual volume and the spatial distribution of rainfall in the country. According to Abdalla, (2002) the southwesterly winds are by nature thermally unstable and therefore when properly triggered are able of encouraging large scale vertical motion. On the other hand, Giannini *et al.* (2003) attribute the recent drought of the Sahel to warmer-than-average low-latitude waters around Africa, which by favouring the establishment of deep convection over the ocean, weaken the continental Discontinuity associated with the monsoon and engender widespread drought from Senegal to Ethiopia.

2.1.4 **The Mediterranean depression:**

The presence of warm SSTs in the north Atlantic region leads to the weakening of the Azores anticyclone and frequent passage of depressions throughout the Mediterranean and hence the ITDZ move to the north.

2.1.5 Easterly waves and associated jet streams:

During summer the TEJS develops in the upper Troposphere just north of the position of the ITDZ. According to El Tom, (1975) a jet stream is defined as a narrow band of air, a few hundred miles wide, moving at velocities of up to 500 miles (about 800 km) per hour in the upper part of the Troposphere. The TEJS originates over central Asia due to the thermal effects of the Tibetan Plateau and extends westward and appears as a minor jet over West Africa. The thermal gradient between central and northern Sudan intensifies the TEJS and it almost intensifies at the same position as in June, with a mean easterly component of 30 m/sec. This jet stream plays an important role in the convection of the cumulonimbus clouds and leads to even distribution of rainfall. The influence of the TEJS is mainly attributed to the fact that the stream is capable of creating contrasting vertical motion within relatively short distances. The core (centre) of the TEJS is usually associated with stronger upward motion and vise versa in northern margin.
Early establishment of the TEJS over Sudan is associated with low rainfall over the Ethiopian Plateau and high rainfall over Sudan from May to July which is attributed to the advection clouds. Late establishment of the TEJS (during August) is associated with high rainfall in the Ethiopian Plateau from May through July and rainfall over Sudan is caused by local convection clouds (Abdalla, 2002).

2.1.6 Meso-scale systems:

According to Okoola, (1999) the meso-scale systems are thermally induced and they are strongest when the thermal contrast is greatest. Meso-scale influences may arise from land–sea contrast, sloping terrain and frictional drag and others. Neither Sudan nor its immediate vicinity includes extensive water bodies. Mountainous areas namely Jebel Marra, Nuba Mountains and the Red Sea Hills constitute less than 3% of the area of the Sudan (El Tom, 1975). Generally rainfall distribution in the country shows marked negative correlation with Latitude and the general decrease is from southwest to northeast i.e. following the direction of the rain producing winds. However, the existence of the mountainous areas and the Ethiopian Plateau tend to interrupt the smooth flow of the isohyets with marked northward shift in such areas and the rain shadows dominate the eastern sides of the high lands. In addition to that the deflective action of the Ethiopian Plateau changes the southwesterly winds into northerly winds and hence the moist winds cover larger area over eastern Sudan (El Tom, 1975). Another effect is produced by the Sudd area where the existence of relatively large water body and vegetation reduce temperature in the region and consequently thermal uplifting is reduced and hence rainfall is also reduced in this area.

2.1.7 Teleconnections:

Several scientists have believe that there are teleconnections between precipitation in drylands and the unusual meteorological conditions in the other parts of the world. For instance, Balling, (2004) suggested a strong linkage between precipitation in the Sahel and the appearance of strong hurricanes striking the eastern coast of North America. According to Osman and Shamseldin, (2002) the El Nino Southern Oscillation (ENSO event) is one of the factors that can cause abnormalities in the behaviour of the ITDZ.

2.1.8 Anthropogenic influences:

According to Zeng, (2003) beside the major effects attributed to changes in large scale atmospheric circulation, anthropogenic factors like overgrazing and agricultural expansion are also causative factors for drought. Such anthropogenic factors tend to increase surface albedo (less sunlight is absorbed) and reduce moisture supply to the atmosphere and consequently lead to less precipitation.

2.1.9 Climate Change (Global Warming):

Climate Change is likely to speed up the global hydrologic cycle, and lead to increased incidence of both floods and droughts (NSF, 2003). According to the Intergovernmental Panel on Climate Change IPCC, (1998) developing countries are highly vulnerable to Climate Change because many of them are located in the dry and semidry regions and also to their inability to adjust or implement suitable adaptation measures.

According to Frederick, (1997) less and more variable rainfall is anticipated in lower latitudes and hence a major influence is expected for the hydrology of dry and semidry regions. This accompanied by the increase in temperature will result in increasing of the frequency and severity of droughts.

Using MAGICC/SCENGEN software, Kordofan states were projected to witness higher temperatures and less rainfall. For instance the mean annual temperature is expected to increase by 1.2^{o} C and the mean annual rainfall to decrease by 5.8% by the year 2030 for Obied (HCENR, 2003).

3.0 Rainfall distribution in the Sudan:

According to Ward and Robinson, (1990) knowledge of temporal and spatial patterns of rainfall is essential to the understanding of soil moisture status, groundwater recharge and surface runoff (river and wadis).

Osman *et al*., (2001) studied the effect of the ENSO event on rainfall variability in Sudan. The results show that the areal annual averaged rainfall values decreased markedly since early sixties with strong co-existence between driest years and the ENSO event. Similar results were obtained by Adam, (2000) who estimated a decrease of 19% in the rainfall of dry lands comparing the two rainfall averages of (1941-1970) and (1970-1999).

According to MOIWR, (1999) the country is divided into three distinct rainfall zones:

The northern half of the country which extends from Khartoum where rainfall is about 200 mm per annum to the Sudanese–Egyptian borders where rainfall is almost nil. In this region the rainy season is limited to 2–3 months with the rest of the year virtually dry. Rainfall usually occurs in isolated showers. The coefficient of variation of the annual rainfall in this northern half of the country may be as high as 100%.

The quarter of the country south the above region is characterized by an annual rainfall of about 700 mm and the rainy season extends for 4 months from July to October. It is worth mentioning that in this quarter of the country rain fed agriculture is mainly practised. And since the coefficient of variation of the annual rainfall is about 30%, the area cultivated and the productivity varies widely from one year to the other (MOIWR, 1999).

Rainfall exceeds 700 mm per annum in the southern quarter of the country where it is dominated by extensive wetland and inhabited by the tsetse fly and other insects which are hazardous both to humans and livestock. Fig (1) shows the isohytal map of the Sudan for the period 1971- 2000.

Although the movement of the rainy season over the country shows marked variation in time, for practical reasons a single general rainy season is recognized for the country. According to El Tom, (1975) by grouping the months during each of which at least 10% of the mean annual precipitation is experienced everywhere in the country; the months of July, August and September were found to constitute the rainy season.

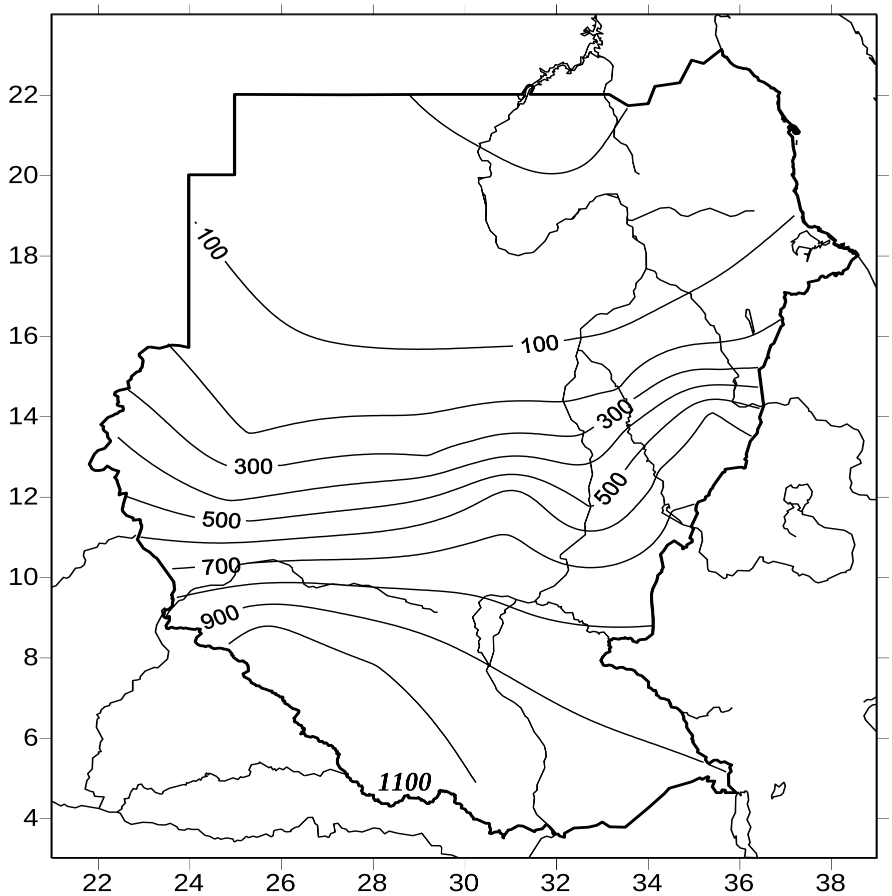

Fig (2.1): Sudan normal rainfall (mm) (1971-2000)

Source: Ahmed and Naggar, (2003)

4.0 Rain producing clouds:

Thermal uplifting occurs in narrow conventional currents and the clouds so developed are capable of attaining great heights and depths and limited horizontal expansion and characterized by having extremely heavy downpours. In tropical countries including Sudan the main rain-producing clouds belong to the vertically-developing group and are mainly of the cumulus and the cumulonimbus types. Rainfall is either produced by isolated rainstorms or by a group of rainstorms. In the latter case several cumulonimbus clouds may organize in distinct lines (line storms or line squalls) (Ward and Robinson, 1990). Thermal uplifting causes the moist southwesterly winds to reach the zone of upper easterlies which are moving against the direction of the surface winds and hence the northeastern lightening (locally known as "Abbadi") is initiated. This sign is reputed as an unfailing indicator of rain-producing storms in the Sudan. According to El Tom, (1975) the mechanism of formation of line squalls seems to be associated with topography particularly the Ethiopian Plateau.

According to Abdalla, (2002) widespread thunderstorms occur due to an unstable stratification composed of the advection of southwesterly monsoon that is overlaid by cool moist southeasterly which in turn is overlaid by the drier north easterlies.

Milford and Dugdale, (1987) described the use of Meteosat thermal infra-red (TIR) data to study storm characteristics over Sudan for the 1986 rainy season. The study revealed the following:

- The largest group of storms was associated with the mountainous parts of the Sudan and Ethiopia; they usually remained close to the mountains but often grew and affect the lower areas to the west.
- Another group of storm originated in the flatter central parts of the country.

The authors described a rainfall estimation methodology in which the basic rainfall estimator is the presence of cloud temperature below a particular threshold and rain gauge data are used to calibrate satellite estimates. Milford and Dugdale, (1987) concluded that the cold cloud duration (CCD) method provides useful information for the Sudan. However, further studies are recommended to improve accuracy.

5.0 Rainfall prediction:

Due to the fact that the physical and mathematical laws that govern the atmosphere are numerous and complicated especially in the long and medium terms, climate prediction is a serious challenge to scientists. During the sixties of the previous century and due to the advancement in the use of computers in meteorology, serious studies were executed in climate prediction. Currently extensive research is being conducted around the globe to improve accuracy of prediction (El Gamri, 2005).

The following is a description of studies on two types of rainfall predictors these are namely the ENSO event and global SSTs.

5.1 ENSO Event:

Peruvian fishermen have recognized El Nino as the appearance of unusually warm water in the tropical Pacific Ocean. The name El Nino (Spanish word) means "The Little Boy or The Christ child" was used because of the tendency of the phenomenon to occur around Christmas. According to Salinger, (1992) during El Nino warm surface water from the western equatorial part of the Pacific Basin invades the eastern equatorial region. On the other hand, La Nina (means The Little Girl in Spanish) is the enhancement of the cold pattern along the equator through drag of the warm surface water westward by easterlies and the mutual upwelling of cold water from deeper layers along the coasts of South America and the Equator. Such oceanic phenomena occur due to interaction between the surface of the ocean and the atmosphere. The linkage of these oceanic phenomena to the global atmosphere is the so-called Southern Oscillation (S.O.). This concept constitutes a major step towards the understanding of the global climate system (Abdalla, 2002).

The S.O. is an exchange of mass between two centres of action, the permanent area of high pressure in the southeastern Pacific (represented by Tahiti) and the lower pressure in the Indonesian region (represented by Darwin in Australia). When atmospheric pressure is higher than average in Tahiti, it is lower than average in Darwin and vise versa. A frequently used index of the S.O., known as the Southern Oscillation Index (SOI) is defined by Salinger, (1992) as: the difference in the normalized pressure anomaly Tahiti minus Darwin. During La Nina SOI is highly positive and it is negative in El Nino phase. The two phenomena (El Nino and La Nina) in addition to SOI are grouped into the so-called El Nino Southern Oscillation or The ENSO event. Due to the absence of continental influence (seasonal reversal winds) comparable to Asia, the annual cycle of SSTs in the Southern Pacific is significantly less than that of North Pacific (WMO, 1999).

There is very little skill in predicting the onset of El Nino; however once it has started, the subsequent evolution over the next 6-9 months can be predicted reasonably. It is worth mentioning that such events can last for twelve months or even more. Several different theories try to illustrate the way El Nino works but none of them has given real skill in making a forecast in advance (NOAA, 2004). Linkages between El Nino and climate anomalies are stronger in the South Pacific and southern continents. For instance, during El Nino rainfall is above average in parts of Peru and Equator, below average in New Guinea and Indonesia and southern Africa. On the other hand, La Nina produces the opposite climate variation from El Nino. However, since 1975, La Nina is only half as frequent as El Nino (NOAA, 2004).

Recent studies show that the African continent shows strong ENSO signals in southern, eastern, and the far north and a notable signal in the Atlantic coast around the Equator and the Sahel. On the other hand, different parts of eastern Africa (including Sudan) show correlation with El Nino event but with differences in magnitude and direction (WCRP/CLIVAR, 2002).

Much of the recent forecast efforts are based on the ENSO event. This is attributed to the relatively longer time scale of variability which allows for predictability of climate that potentially extends for many seasons. It is worth mentioning that an El Nino (or La Nina) event share general characteristics with other similar phases. However, every event is to some extent unique in its magnitude, duration and climate impacts.

Forecast techniques based on the teleconnection with the ENSO event are capable of producing valuable information that can be used in water resources management and in the reduction of the impacts of drought. Such techniques were used to forecast crop production with 0.71 correlation coefficient (Cane *et al.*, 1994). This information can be used to determine food shortages, crop marketing strategies and planning relief operations.

Cobon *et al.*, (2003a) used the climate analysis package "Rainman International" to forecast Southern Africa rainfall using three months average SOI (in spring) as predictant for the summer rainfall with forecast lead times of 0-2 months. The authors found that during the months August through October an average SOI>5 is associated with above median rain in central South Africa and Zimbabwe and below median rainfall in southern Kenya and Tanzania and the opposite occurred for

SOI<-5. Cobon *et al.*, (2003b) described a methodology of using daily rainfall data for assessing the impacts of ENSO event on the onset and number of rain events. The results showed that a total shift of 14 days is induced and a shift in the median number of rain events (6 for SOI<-5 and 9 for SOI>5) from the climatic median of 7 with a forecast lead time of 0-3 month. The methodology was found to be convenient for decision-making by the farmers. However, lack of long-term (>80 years) of daily rainfall data limits widespread application.

Abdalla and Fota, (2000) studied the correlation between Sudan rainfall and EL Nino/ La Nina episodes and they selected five meteorological stations to represent the different climatic zones of the country. The authors found that the western and central parts, as represented by Fashir and Wad Madani respectively, in most cases showed below-normal rainfall during El Nino years and above-normal during La Ninas. The eastern part as represented by Eddamazin showed normal rainfall during La Nina years and slightly below-normal rainfall during El Ninos of 1958, 1982 and 1983. However, during the last three El Ninos markedly above-normal rainfalls were registered. In the Red Sea coast (Port Sudan) and the southern region (Juba) the influence of the ENSO event was not clear. However, this partly contradicts the results obtained by Osman and Shamseldin, (2002) who argued that the rainfall of both central and southern Sudan showed distinct correlation with the ENSO event.

Abdalla and Fota, (2000) concluded that Sudan rainfall regime is associated with different complicated climate systems, which need serious scientific investigations.

El Gamri, (2005) studied the influence of the different ENSO stages on the rainfall of dry Sudan. The study revealed the following facts:

- Rainfall is found to be above-normal during prolonged La Nina and below normal during prolonged El Nino, with higher forecast skills for La Nina. It is markedly above-normal rainfall during starting and well established La Nina, normal during starting El Nino and markedly below-normal during dying La Nina, dying and well established El Nino.
- The effect of the La Nina stage is direct and concurrent while El Nino works with lag-time.
- Bad rainy seasons start normally.

The last finding is confirmed by Ward, (1999) who concluded that "For Sahel region June rains (early season) are generally good in

El Nino years whereas July–September rains (main season) are reduced".

5.2 Sea Surface Temperatures:

One of the recent developments during the 1990s and because of the mutual influences between the atmosphere and oceans the use of SSTs in rainfall prediction was started. According to Mutemi, (1999) the hypothesis can be stated as "if significant correlation exists between rainfall and SSTs it can be assumed that they will be related in the same way in the future". Hence empirical-statistical rainfall prediction models can be developed.

El Gamri, (2005) used this technique to predict rainfall for some meteorological stations and wadis in central Sudan and the following facts were revealed:

- Using empirical-statistical models and global SSTs as predictors; the highest predictability was found in Kassala meteorological station while the least was found in Khartoum meteorological station.
- Khor Abu Fargha discharge empirical statistical prediction models excelled those of rainfall prediction. The fact that the models predicted wadi discharges better than rainfall may be attributed to the fact that wadi discharge data represent the whole catchment area of the wadi while rainfall data represent only the rain gauge readings at the particular station (El Gamri, 2005).

According to Abdalla, (2003) the Sudan Meteorological Authority (SUMA) has started to issue seasonal rainfall forecast since the year 1999 the most important of which is the rainfall forecast for the period June through September which constitutes the main agricultural season in the country. Using the Principle Component Analysis the country was first divided by SUMA into 6 homogenous rainfall zones. Abdalla, (2003) concluded that the results of SSTs–rainfall regression models are reasonable and can be used in strategic planning in the different sectors including food security, environmental protection and disaster mitigation. On the other hand, early warning of favourable climatic conditions can be useful to improve productivity in rain fed agriculture since the usual practice is to use low inputs and drought resistant crops and hence, the full benefit of the favourable climate is not captured (Cobon *et al*., 2003b). However, Osman and Shamseldin, (2002) argued that combination of forecast models would normally improve the quality of the prediction.

Concluding Remarks:
In the Sudan rainfall plays a vital role in the environment and socioeconomic conditions. However, annual averaged rainfall values decreased markedly since early sixties. It varies from almost nil in the North to about 1500 mm at the extreme Southwest and consequently two-thirds of the country lie within either the dry or semidry regions. The months of July –August-September were found to constitute the general rainy season of the Sudan. The major factors influencing the rainfall of the country include; climate change, the position of the ITDZ, the anticyclones around Africa, monsoonal winds, teleconnection with the ENSO event, the TEJS and the Mediterranean depression. Other factors include meso-scale systems and anthropogenic influences. Contrary to El Ninos rainfall of the Sudan is found to be generally above normal during La Ninas. The effect of the La Nina stage is direct and concurrent while El Nino works with lag-time. Meanwhile, bad rainy seasons were found to start normally. The use of global SSTs as predictors gave satisfactory results however, combination of forecast models is advocated to improve the quality of prediction. The prediction information were used in strategic planning in the different sectors including agriculture, food security, environmental protection and disaster mitigation. Generally, Sudan rainfall regime is associated with different complicated climate systems, which need serious scientific investigations.

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