ISSN 2350-1049

International Journal of Recent Research in Interdisciplinary Sciences (IJRRIS)
Vol. 10, Issue 4, pp: (7-16), Month: October - December 2023, Available at: www.paperpublications.org

Reviewing Indicators of Climate Change and Their Environmental Impacts in Sudan

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Published Date: 16-October-2023

Abstract: **This research aims to review climate change indicators and their environmental impacts in Sudan, based on relevant published scientific research results. Climate change is a global problem but an ancient, recurring natural phenomenon. The early Holocene period over the Nile Basin was wetter than it is today, and historical fluctuations in precipitation occurred, which was reflected in its drainage, as the precipitation bands migrated latitudinally over the middle Nile by about 600 km during the past 20,000 years. Recent climate data for Sudan for 30-50 years shows an increase in temperature and a decrease in rainfall and confirms a change in the pattern of relative humidity, clouds, radiation, and evaporation. Rain depletion was more severe in central, semi-arid Sudan, where in the periods 1921-1950 and 1956-1985 the annual rainfall rate decreased by 15%. Also, there was a contraction in the length of the rainy season by three weeks, and a migration of the rain zones southwards by about 100 km. The summer rains have decreased in western and southern Sudan by 10-20% since the mid-seventies, with the observed heating exceedingly only one degree Celsius, which is equivalent to 10-20%. These changes in Sudan's climate have resulted in the deterioration of about 120 million hectares of land including 64 million hectares of different soil types to varying degrees; changes in biological factors causing the deterioration of soil resources and thus the deterioration of grain production; scarcity of tree products; deterioration of Gum Arabic production; general deterioration in the natural production base and in renewal of natural resources; deterioration in the irrigation systems; and the expansion of the desert's environment. Reducing climate change impacts requires an effective membership of Sudan in the international action systems combating climate change, and formulating lines of local and regional cooperation to keep pace with developments in climate change.**

Keywords: **Sudan, environmental fragility, climate change, environmental degradation, global cooperation.**

1. INTRODUCTION

Most of Sudan's territory is located within the arid and semi-arid regions of tropical Africa, where the humid part lost most of its area after the secession of South Sudan in 2011 AD. These arid and semi-arid regions are characterized by climatic characteristics, the most important of which is the fluctuation and irregularity of rainfall amounts during the rainy season, with high average seasonal temperatures and annual evaporation rates. The global climate has witnessed clear climatic changes in recent decades as a result of many reasons related to industrial progress and population increase, which has had a negative impact on many parts of the world, including the areas in which Sudan is geographically located. There is much scientific evidence confirming the occurrence of climate change in Sudan and the consequent environmental impacts. This will be the concern of this research based on relevant scientific research.

2. INDICATORS OF CLIMATE CHANGE IN SUDAN

Tropical Africa, which includes Sudan, has witnessed climatic changes confirmed by radiocarbon dating and analysis of micro-fossil plants of tropical lake sediments. The early Holocene was wetter than it is today across the entire tropical region, in contrast to the last glacial maximum, which was cold, dry, and windy. Evidence has been found of wetter conditions on the Red Sea Hills at that time compared to today, and this also applies to most of North Africa (Mawson, et al., 1984). Records in eastern desert lakes show that early Holocene oscillations affected the water levels and salinity of the hydrological systems of these isolated lakes as much as they were isolated from larger groundwater systems (Hoelzmann et al. 2010). In the Mansurab Valley, which is 15 km west of the lower White Nile, and which lies within the dry range of present-day north-western Sudan, semi-aquatic shells have been found in the silt and clay of the shallow depression (Williams et al. 2011). This is linked to the early Holocene, which confirms that the climate was humid with a strong indication in this part of Sudan. This also matches shells found east of the lower White Nile. These results confirm that wetter regional conditions were associated with times of high Nile flow in the early Holocene (Williams et al. 2011).

Historical fluctuations in precipitation occurred over the Nile Basin, which was reflected in its drainage, as precipitation zones migrated latitudinally over the Middle Nile by about 600 km during the past 20,000 years. Decadal changes in precipitation occurred during the twentieth century and reached 20% of the changes that occurred in the Holocene. This reflects the sensitivity of the Nile Basin to many factors operating at different times as well as spatial dimensions that include changes in the Earth's orbit, global ocean temperature anomalies, ITCZ migration, and land cover changes across the African continent (Hulme, 1994).

The swamps of South Sudan (Sudd) work to change the local energy budget by increasing the flow of latent surface heat. Their presence leads to a lower ground temperature (up to 2 degrees Celsius), a large thermal gradient extending from north to south, and an increase in the local rainfall rate (Up to 40%). Particularly important is its effect on rainfall in neighboring regions. Such effects were not found mostly on rainfall over the source region of the Nile in Ethiopia or in the Sahel region, but they are appropriate for the humid conditions over central Sudan (up to 15%) compared to the conditions of bare desert soil (Modathir et al. 2013).

The Sudanese Sahel region is characterized by being an arid to semi-arid region. It relies on seasonal rains as the primary source of water, and its rains have interannual variability, as rain fluctuations are linked to the moisture transfer process. The main origins of most of the air masses that reach this region during the monsoon period are over the Arabian Peninsula and Central Africa (not the country), or they are linked to the eastern tropical jet. The flows associated with the movement of the ITCZ contribute half of the amount of water falling into it, most of which comes from Central Africa. This suggests that moisture recycling is the main contributor compared to oceanic sources. Flows from the northeast (the Arabian Peninsula and northern Asia) and the east (the Horn of Africa and the northern Indian Ocean) contribute about a third of the falling water. The remaining waterfall comes from the Mediterranean Sea and the West Coast with smaller contributions, and the different sub-regions of the Sudanese Sahel have different sources of moisture (Salih, et al. 2015).

There is a significant increase in temperatures over the whole of Sudan, with a significant decrease in rainfall rates in the northern half of it. The correlation between temperatures and irregular rainfall confirms the frequent occurrence of droughts. In contrast to the assumption of a return to drought that lasted for a long period in the African Sahel region, the results for Sudan indicate a high level of drought. The frequency of occurrence of drought categories during the period 1975-2008 ranged from 44.1% - 70.6%, compared to frequencies that ranged between 8.8% - 40.0% for the period 1941-1974 (Elagib, et al. 2011). Climatic data for Sudan for a period of 30-50 years, show an increase in temperature and a decrease in rainfall. It also confirms a change in the pattern of relative humidity, clouds, radiation, and evaporation, a trend that may accelerate environmental degradation and desertification in Sudan (Alvi, 1994).

Annual trends in average temperature during the period from 1950 to 2020 in Sudan show peaks of increase during each decade, and there is fluctuation in annual average temperatures during each decade of this time period (Figure 1). Likewise, important decadal trends appear during this period 1950 -2020, divided into three decades, increases in average temperatures (Figure 1). This is confirmed by the observed and expected temperature increase for the period 1960-2039 (Figure 2), which ranged between less than 0.5 and 1.3 degrees Celsius. Before that, since the 1940s, there was an increase in annual temperatures and wet season by 0.076-0.20 and 0.082-0.29 degrees Celsius/decade (Elagib, et al. 2000). The period of greatest warmth in Sudan appears to be linked to the dissipation of rain that was recorded after the mid-1960s. A general increase in the coefficient of variation of monthly temperatures during the year was also observed, which is more significant in the northern and central locations of Sudan (Elagib, et al. (2000).

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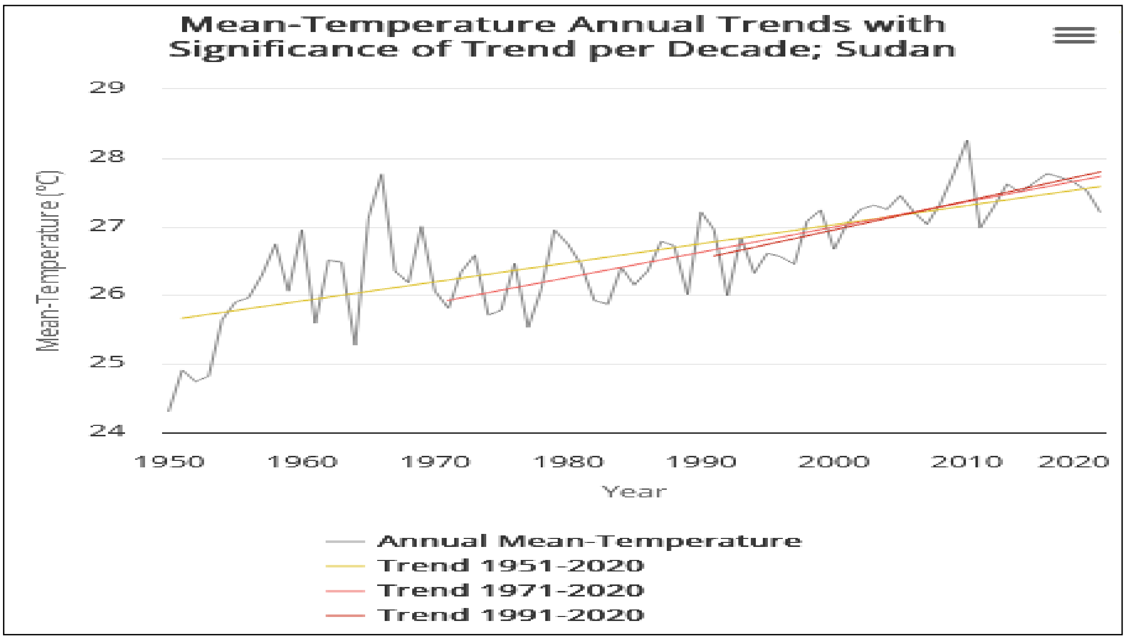
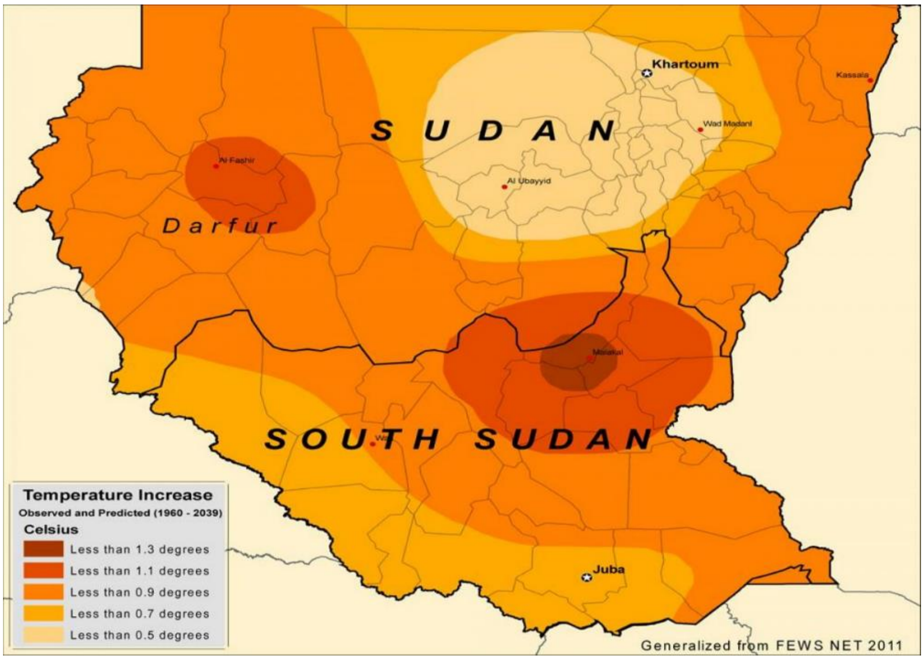


Source: https://climateknowledgeportal.worldbank.org/country/sudan/trends-variability-historical

Figure 1: Annual trends in mean temperature with a significant decadal trend in Sudan 1950-2020



Source: UNFCCC

Figure 2: Observed and expected increase in temperature on the Celsius scale from 1960-2039 in Sudan

Studies on climate change and land use/land cover along seasonal migration corridors for livestock in the Gedarief region in eastern Sudan have confirmed a degree of significant warming. There is an increase in irregularity and seasonality of rainfall, and increased drought conditions during the beginning and end of the wet season (Sulieman et al. 2012). Evapotranspiration over the Sudan responds more to heating and drought conditions, as it showed increasing rates, especially during the rainy season. It appears that the extent of the increase has decreased with the decrease in the period of sunshine, solar radiation, and the irregular behavior of wind speed. There have also been changes in the observations of monthly fluctuation during the year, which suggests an increase in the incidence of extremism (Elagib, et al. 2000).

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Ayoub (1999) compared rainfall for a long period of time in four sub-regions in Sudan, where it became clear that the decrease in rainfall amounted to 30-40%. The parts of western Sudan (Kordofan and Darfur) witnessed very large anomalies in rainfall compared to the central and eastern parts (Gedaref, Butana, and Damazin), and they suffered from great periods of intermittency compared to the eastern and central parts. The decadal rainfall averages showed lower than the average rainfall for the last three decades in these four sub-regions. Rain depletion was also characterized more severely in central, semi-arid Sudan, in the period 1921-1950 and 1956-1985 when the annual rainfall rate decreased by 15%, and there was a contraction in the length of the rainy season by three weeks, and the rain zones migrated towards the south by about 50 and 100 km. This is due more to the low frequency of rain events than to the low rainfall productivity associated with each “rain event” (Hulme, 1990).

The annual time series south of 16°N mostly follows the rainy season time series, with the exception of the zone north of it that shows a real change in the temperature time series. There are clear rising trends in the time series of wetness and hot seasons in the rest of the country, and their trends are characterized by rising. The periods 1941-1970 and 1951-1980 were also distinguished by their significant difference from the periods 1961-1990, 1971-2000, and 1981-2010, as they were the wettest. This was evidenced by the indicators of the beginning of a new increase in rainfall in the period 1981-2010 (Mohamed, 2018). Summer rains have decreased in western and southern Sudan by 10-20% since the mid-seventies, with the observed heating exceedingly only one degree Celsius, which is equivalent to (10-20%) (Mohamed, 2018).

It is likely that the temperature and wetness rates will rise over the Dinder River, which is sensitive to these two climate factors that are likely to rise in this century (Basheer et al. 2016). By so, the climate above it will become hotter and wetter and its expected flow will become very sensitive to changes in rain and temperature. It is expected to increase so that it positively affects the ecosystem of the Dinder River Park and not just the river. This may improve the process of ecological restoration of plant and animal habitats in it (Basheer et al. 2016). Similarly, the archive of satellite and aerial images of western Sudan has shown short-term trends during the period 1943-1994 in tree abundance despite many decades of drought in the region. Despite the return of plant population turnover, this is not yet considered an indicator of recent climate changes in this region (Schlesinger et al. 1996).

3. ENVIRONMENTAL IMPACTS OF CLIMATE CHANGE IN SUDAN

Climate change manifested itself in the indicators of rising temperatures, fluctuations in rainfall, and repeated waves of drought, causing severe impacts on different life forms (Nadeau, et al. 2007; Ye, et al. 2018); and on different regions and social groups (Watson, et al. 1996), and has led to a decrease in natural vegetation, accelerating desertification (Fu, et al 2017), environmental degradation and loss of biodiversity (Wang, et al. 2017) as changes in vegetation structure and land cover (Klein, et al. 2007), especially in dry regions (Yu, et al. 2018, Xie, et al. 2016). There is evidence that warming during the twentieth century has been faster than shifts in species ranges (Houghton, 1990), potentially leading to widespread loss of biodiversity (IPCC, 1996).

Drought areas in East Africa are expected to increase by 16%, 36%, and 54% under Representative Concentration Pathways (RCPs) and by 2.6, 4.5, and 8.5, respectively by the end of the twenty-first century (Gebremedhin et al. 2020). Also, since the end of the 1960s, the West African Sahel region (10-18 degrees north) has witnessed a continuous and often severe drought, and it is considered among the most extensive climate changes on a regional level and unquestioned over the last half-century (Bell et al 2006). Sudan as part of both these regions is not exceptional, and is considered the most vulnerable (Gebremedhin et al. 2020) as the observed climate change in Sudan has exacerbated drought conditions (Elagib et al. 2000). The interaction of endemic poverty, and environmental systems deterioration, complex disasters, conflicts, and the limited availability of capital, markets, infrastructure, and technology are essential to exacerbate climate change impacts in Sudan (Zakieldeen, 2009). Also, the key aspects of the vulnerability of Sudan's savanna range to drought including environmental fragility, institutional weakness, high levels of poverty and food insecurity, and economic and political instability, all of which have been exacerbated by climate change (Callo-Concha et al. 2013). Rapid population growth and the expansion of agriculture and nomadism under a changing climate budget could dramatically increase the number of “at-risk” citizens in Sudan in the next 20 years (Funk et al. 2011).

Various early studies predicted the decline of vegetation in most areas of Sudan (Stebbing, 1972). In western Sudan, Acacia “Hashab” trees grow as part of the agro-pastoral system, which has been able to resist for hundreds of years in Kordofan Governorate, where 70% of gum Arabic is produced. Gum Arabic production in Sudan deteriorated sharply after the long drought that extended between 1979-1985, as many trees were lost due to drought and pests. Farmers report that the deterioration in gum Arabic production is largely due to the “unfavorable” nature of social-economic relations, the role of which drought exacerbated and led to the deterioration of the production of the agricultural-forestry system. The inability to obtain a fair price at the local level and an overemphasis on cash economics to ignore the components of the “tree” have resulted in a system in which Gum Arabic gardens have flourished with intensive orchard cultivation by small farmers. The “Hashab” tree disappeared as soon as farmers were no longer able to care for it (Huntinger, 1993). Financial and business risks can have serious impacts on farmers' decisions and farm income. Farmers can also be more risk-efficient and obtain higher incomes by adopting more diversified agricultural systems and applying the proposed improved practices (Mustafa, 2006).

The Kordofan region contains diverse forest species (more than 180 species of trees and shrubs), both local and exotic. Threats to these forests include drought, soil factors, use of fire, grazing, expanding agriculture, illegal logging, lack of awareness about the problems of deforestation, and insufficient forest awareness. Genetic erosion has occurred in most parts of the natural forests in Kordofan (El Tahir et al. 2010). The central region of North Kordofan provides the necessary natural resources for “nomadic” agricultural and pastoral activities. The unjustified use of these resources has led to their degradation and destruction. Desertification also excluded much of the land from production at a time when the population and demand for land were increasing. Environmental damage also included water shortages and the change in the pattern and timing of seasonal rainfall, as collective grazing increased, which led to overgrazing, and increased logging for the purposes of making charcoal and building homes, where women are considered the most affected (Badri et al. 2000).

The decrease in the abundance of herbs in the Port Sudan area in 2020 AD can be attributed to the very high temperatures after 1998 AD (Loh et al. 2020). Similarly, more areas were affected by desertification and desert encroachment in the Abu Zabad locality in western Sudan (Abbas et al., 2018). Despite this, long-term desertification/the return of the growth of natural vegetation cover over time and space in the center of North Kordofan State was estimated and found that desertification during the last 21 years has helped the return of natural vegetation growth in the areas around rural villages (Dawelbait et al. 2012

Climate change in Sudan has led to the deterioration of the environmental ranges in the period between 1985 - 2020 (Figure 3), as for example, the desert range expanded by more than +11.0%, from 177,308 km2 in 1958 to 314,076 km2 in 2020 (Figure 3), and similarly the rest of the ecological ranges (+6.8% for semi-desert), except for the ranges of upland and wetland plants (Nadir et al. 2016). Various studies indicate the deterioration of about 120 million hectares of land, including 64 million hectares of different soil types to varying degrees (Ayoub, 1998).

There are many applied studies that help explain this deterioration as a result of climate change. In Dar es Salaam locality, North Darfur state, the percentage of crawling sand increased successively by 29% (868 km2), then to 36% (1035 km2), then to 39% (1132 km2) during the period from 1970-2018 (Al-Zubier et al. 2019). In North Kordofan State, the NDVI index for the degree of greenness of vegetation and its relationship to rainfall showed low values in three of the eight seasons under study (Elton et al. 2019), and the results confirmed that the sand on Khor Abu Habil advanced by 4% in 2000 and 13% in 2020. (Ahmed et al. 2022), and the Blue Nile forests deteriorated in the quality of trees, as many of the species that were prevalent in the past decreased and others disappeared, such as *A. seyal vor fistula*, and the area of these forests decreased from 14.7% in 1973 to 3.1% in In 2016 out of the total area of the region (Al-Zubier et al. 2020), and in the Ashaad and Setrab regions of the Red Sea State in Sudan, the vegetation area decreased from 192.38 square kilometers to 187.39 square kilometers and then to 148.59 square kilometers between the years 1987, 1999, and 2013, respectively (Al-Zubier et al. 2020), similarly, the Halba region in White Nile State lost 91% of its tree and forest cover, which represented 41% of its area, and the area of natural pastures decreased by 16.55% in the period between 1973-2014 (Wadi et al. 2017). In the Butana area, a peak of natural vegetation was found in the year 1850 AD, which had the ability to carry the natural vegetation, environmental imbalance began in 1970 AD, and the changes occurred during four successive stages, evident in the dynamic deterioration of the vegetation cover, the decrease in rainfall rates, and the decrease in the carrying capacity (Alredaisy et al. 2011), and likewise it became clear that the deterioration of acacia trees (Acacia) in the West Butana region is due to a decrease in annual rainfall rates, among other factors, including agricultural expansion, which contributed by 40% to it (Alredaisy et al. 2011). The instability of climate factors and the change in biological factors have led to the deterioration of soil resources and thus the scarcity of tree products in the Qadmabila area in Gedarief State (Idris et al. 2015).

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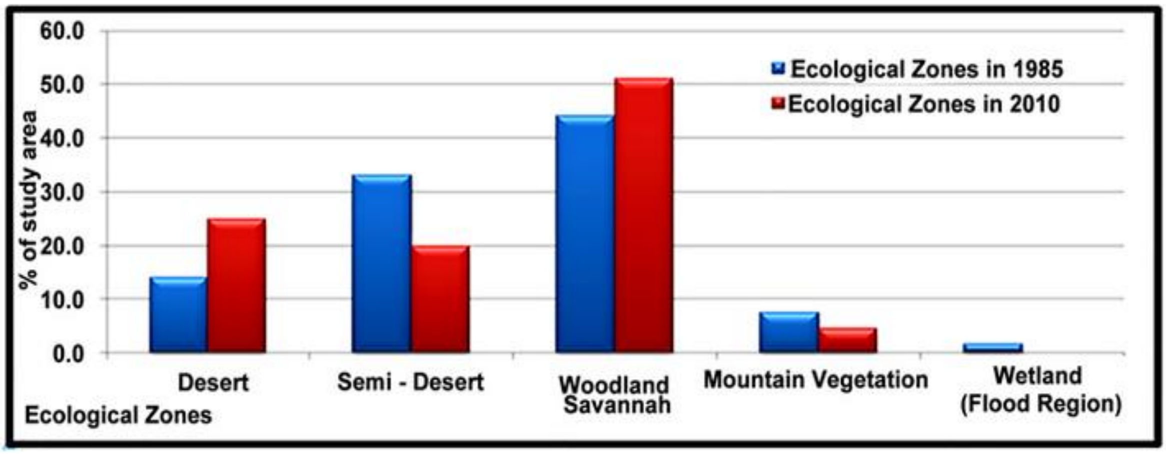

Source: Nadir et al. 2016

Figure 3: Environmental ranges in 1985 and 2010

Land degradation and desertification processes have increased in arid and semi-arid environments in the last four decades (Salih et al. 2017). Land degradation can lead to climate change, as high temperatures, low rainfall, long periods of sunshine, cosmic radiation, and high rates of evaporation-transpiration, especially during the wet season, have been observed, in addition to changes in the oscillation of annual and monthly observations (Elagib et al. 2000). Mechanized agriculture projects in the Gedarief region are considered a major cause of environmental degradation and land loss, in addition to environmental complications such as drought. Forests have turned into agricultural lands, accompanied by unorganized cutting, which is considered the main factor contributing to land degradation in the Gedarief region. In addition, contradictory sectoral policies affect land ownership (Glover et al. 2012). In light of such factors, there is evidence that confirms the consequences of dry farming of lands in the Gedarief region for decades, which led to rapid changes in land use and land cover due to agricultural expansion, government policies, and drought.

The agricultural sector suffers from climate fluctuations. This situation worsened further after the discovery of oil and the focus on investment and petroleum-related industries (Mahgoub, 2014). The negative impact of the potential climate change falls on food availability and connectivity in Sudan. The most affected are the poor families along with the deterioration in the country's economic performance (Sassi et al. 2013). Climatic change significantly led to changes in the pattern of land use, land cover, and soil physical and chemical properties. These changes contributed to land degradation and low soil productivity (Biro et al. 2013). In Sudan, deep plowing and leveling of the surface soil in rain-fed agricultural areas increased its exposure to wind erosion. This has caused a decline in soil fertility and the formation of sand dunes in some places. The impacts of these practices on the natural resource base have included environmental degradation, food insecurity, and a sharp increase in income inequality among Sudanese producers (Abadi et al. 2013).

There are important changes in climate conditions, soil characteristics, and natural vegetation in the Butana region, as the size distribution of soil particles changed to a high degree, especially in the silt layer, and a slight change occurred in alkalinity - acidity (Meheissi, et al. 2010). The Butana region was affected by the fluctuation of Climate change in renewing its natural resources, including the soil resource, as it is characterized by a "soft" balance between climate and ecosystem, which is what characterizes the Sudanese Sahel region, of which it is a part (Elhag et al. 2009). Likewise, the Gash Delta scheme has been affected by climate fluctuations, on which a large number of ethnic groups rely to live and be self-sufficient, and have different production strategies, some more successful than others. Since the 1980s, a clear deterioration in the irrigation system in this scheme began with a decrease in the areas available for agriculture and a general deterioration in the natural production base, which affected these ethnic groups (Kirby, 2001).

Climate change in Sudan has also caused a shortage of drinking water in its arid and semi-arid parts. It began to take a critical situation in the 1940s of the last century when population density increased around water sources. Consequently, there were increased concentrations of humans and animals, environmental deterioration, and removal of vegetation. The government adopted a number of ambitious projects to improve rural water sources in Sudan, which differ from one region to another. In dry areas, improving these sources may mean increasing the amount of water, and in less dry areas it means more than just water quality. The imbalance between the amount of water required for healthy living and real consumption is considered the central problem of rural water supply in Sudan (Mohamed et al. 1985).

4. CONCLUSION

This research worked to review climate change indicators and their environmental impacts in Sudan. Climate change occurred in early geological periods and is still occurring there as there was an increase in temperature and a decrease in rainfall; a change in the pattern of relative humidity, clouds, radiation, and evaporation, rainfall depletion; a contraction in the length of the rainy season; and a migration of the rain zones southwards. The impacts are quite varied including, not exclusively, the deterioration in lands and soils; the renewal of natural resources; the expansion of the desert area, semi-desert, and dry savannah; the Gum Arabic production; the grain production; the tree scarcity; and the tree products. Importantly, there is environmental conflict over resources (Verhoeven, 2011).

Combating the impacts of climate change in Sudan requires an effective membership in the international action systems combating climate change. Since Sudan does not differ from other developing countries in its high degree of exposure to climate fluctuation and change (Zakieldeen, 2009), there is a need for regional cooperation to keep pace with developments in climate change information, and a local line of combating programs that consider the human factor including visions and aspirations of the contributors to how these combating programs integrate together (Davies, 1986), not the authoritarian visions.

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