Extreme rainfall events over Accra, Ghana, in recent years

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Abstract

This study examines the recent changes in extreme rainfall events over Accra, Ghana. For this study, an extreme rainfall event is defined as a day with rainfall equal to or exceeding the 1980-2019 95th percentile. Knowing extreme rainfall events help to identify the years with the likelihood of rainfall-related disasters in Accra. In addition, it helps to identify the years with the likelihood of drought or severe dryness which are critical for the livelihoods and economic activities of the people. The study used rainfall data from rain gauge for Accra and satellite-derived winds at the 850 hPa level over southern Ghana from 1980 to 2019. It compares these climatic parameters for both pre-2000 and post-2000 to find out the changes that have occurred throughout the study period. Results show that the frequency and magnitude of extreme rainfall have generally increased during the post-2000 period than during the pre-2000 period, causing increases in mortalities and damages to properties. Seasonally, extreme rainfall events were most intense in July during the pre-2000 period but have changed to June during the post-2000 period. Notably, more intense rainfall events have also occurred during post-2000 winter than pre-2000 winter, consistent with increased warming in the study area. Monthly mean meridional winds at the 850 hPa level were stronger (weaker) in the northerly (southerly) direction during the pre-2000 period but have changed to be stronger (weaker) in the southerly (northerly) direction during the post-2000 period.

Keywords

Extreme rainfall, 850 hPa Meridional winds, Climate Change, Ghana, Accra.

1 Introduction

Precipitation is one of the atmospheric parameters that can be used to assess climate change (Pereira et al., 2020). It can cause worldwide natural hazards when it exceeds tolerable levels (Hallegatte et al., 2013). It is expected that warming climates will significantly induce changes in the distribution of extreme weather events across the globe, thus affecting precipitation patterns. Such usually devastating events include severe drought, extreme rainfall, and flooding (Martel et al., 2018). The early part of this 21st Century saw several research publications on the impacts of climate change and vulnerabilities on humans and natural resources by the Intergovernmental Panel on Climate Change (IPCC) (Few, 2003). Extreme rainfall has caused interruptions to power supply, destructions of farm produce and infrastructure, displacement of communities as well as the outbreak of diseases across many parts of the world. Flooding has led to food insecurity in Asia (Douglas, 2009) and needs innovative developments to cope. According to estimates by Insurance Companies, worldwide losses of property recorded through severe storms, flooding, droughts, as well as climate-related fires reached $60 billion in 1996 and $89 billion in 1998 (Brunner, 2001).

Food security in West Africa heavily depends on rainfall. However, in extreme rainfall, so much havoc is caused, leading to food scarcity. Several communities in Nigeria for example have recently experienced devastating flooding which was attributed to the combined effects of climate change and the neglect of implementing building laws which lead to poor community planning (Iroaganachi & Ufere, 2013). The magnitude and frequency of extreme rainfall due to climate change have increased, warranting intense studies to understand the factors that drive such occurrences (Della-Marta et al., 2007; Mahjabin & Abdul-Aziz, 2020). The chronology of rainfall, such as consecutive dry or wet days, is of high importance for most activities especially those related to water resources. Some societies have tried to reduce the consequences of extreme rainfall events through the improvement in technology and social organization (Kates et al., 2006). The consequences include major loss of population, out-migration, and even the collapse of societies. Ogega et al. (2020) assessed the performance of a model run to investigate heavy precipitation events over East Africa concerning climate change and concluded that there is a possibility of frequent occurrence of extreme precipitation by the end of this 21st Century. It has therefore become necessary for similar studies to be conducted in Ghana to examine the potential impacts that changes in the climate will have, since the perineal flooding in Accra, the largest city and capital of Ghana, usually trap people at unwanted locations whenever they occur (Tabiri, 2015).

Increased urbanization in Accra (Danquah, 2013) has exacerbated the effects of climate change and this is evident through the perennial flooding of the city. Changes in rainfall patterns over Accra have been attributed to climate change by several authors (e.g. Abbam et al., 2018; Asante & Amuakwa-Mensah, 2015; Codjoe et al., 2014; Tettey et al., 2017). The strengths of wind that accompany rainstorms have increased in recent times, becoming more destructive over Accra (Padi, 2017) and its environs. Consequently, in this study, we examine the extreme rainfall events that have been occurring over Accra in recent years. Our results indicate that the frequency and intensity of extreme rainfall events as well as annual rainfall amounts have increased during the post-2000 compared to the pre-2000 climatic era. Meanwhile, mean monthly temperatures for the post-2000 era were also estimated to be above the long term mean of 26°C whilst the pre-2000 era was mostly below the mean.

During the pre-2000 era, the heaviest rainfall was reported to have occurred on 3rd July 1995. According to the United Nations Department of Humanitarian Affairs (UN DHA, 1995), a heavy rainstorm entered into Ghana from the east and affected almost the whole country overnight and exited the country in the morning. It rendered the city of Accra to severe flooding. Official reports indicated that more than 1,500 people were rendered homeless through that severe rainfall event. Other amenities like telecommunication and electrical systems were severely damaged for almost 4 days. The report indicated that there was a lack of preparedness which hindered the provision of relief to the affected people. Meanwhile the post-2000 era recorded its highest rainfall over Accra on 3rd June 2015. The World Bank Group (World Bank, 2017), described the 3rd June 2015 rain disaster as the worst flood in recent history of Accra. Over 154 Ghanaians were reported to have been killed by the downpour and its associated fire that occurred in the city (Emmanuel, 2018; Owusu & Obour, 2021).

2 Effect of Meridional Winds on Rainfall over Ghana

Due to the geographical location of Ghana (Figure 1), the country is affected by two distinct airmasses: the dry continental airmass which brings about the harmattan or the dry season and the maritime airmass which is moist and brings about rain and active storms (Toledano et al., 2009). Wind directions in this study conform to meteorological conventions. The continental airmass is usually northerly in direction, but mostly northeasterly whilst the maritime airmass is southerly, usually southwesterly in direction. However, these airmasses are controlled by high-pressure systems that develop on both sides of the hemisphere, either on the continent of Africa or around the continent (Singleton & Reason, 2007). Ghana is usually under the influence of a low-pressure usually termed as the equatorial trough because it is not too far from the equator. As a Meteorological norm, winds blow from the high-pressure zone to the low-pressure zone and that is why two different airmasses alternatively affects the country.

Ghana is divided into two weather and climate zones which comprise the northern sector and the southern sector (Owusu & Waylen, 2013). The southern sector has two rainy seasons; the major and minor rainy seasons, whilst the northern sector has only one rainy season (Owusu & Waylen, 2009, 2013). These rainy seasons are then followed by the dry harmattan season, which starts in November and eventually affect the whole country till the beginning of the rains in March (Breuning-Madsen & Awadzi, 2005). The major rainy season in the south starts from March to July with a break in August which is usually termed as the “little dry season” (Adejuwon & Odekunle, 2006). Mostly, farmers take advantage of that period to harvest their crops and dry cereals and prepare their lands for the minor rainy season. The minor rainy season then starts in September and ends in November. However, the northern rainy season is prolonged and starts from May end ends in October to give way to the dry harmattan season. There had, however, been times when the harmattan resurfaces during the latter part of March or early April (Lyngsie et al., 2011).

In weather forecasting, the use of meridional (v) and zonal (u)-wind is very important and is mostly used in ensemble forecasts (Pinson, 2012). At the beginning of the major rainy season, winds change from the northerly direction to become southerly and create perturbations in the atmosphere for massive cloud developments that result in heavy rains (Owusu & Waylen, 2013). These rains are very erratic from the beginning of the rainy season, they are mostly accompanied by very strong winds but as the season grows, the windy conditions reduce while the rain amounts increase. There is a clear indication that both northerly and southerly meridional winds strongly influence rainfall over West Africa in general and has a predictive ability that can be harnessed for forecasting purposes (Raj et al., 2019).

Meteorologists have used satellite and model-derived meridional winds at the 850 hPa for forecasting and it has worked well over the years (Ta et al., 2016). Winds at this level influence rainfall over West Africa as they control moisture distribution over the sub-region and also have potential for forecasting. Pineda & Willems (2018) used the US National Centers for Environmental Prediction/ National Center for Atmospheric Research (NCEP/NCAR) reanalysis wind data at the 850 hPa level to determine drivers of extreme rainfall with complex terrains extreme value (EV) models. Meridional wind components have been the main drivers of tropical extreme rainfall events whilst zonal winds have been responsible for the extra-tropics (Pineda & Willems, 2018). Boos & Kuang (2010), observed that zonal winds break down towards the east of India and become meridional due to the effect of the Tibetan Plateau and produce heavy rains in the summer season. The use of meridional winds, even though widely used in other places around the world, have not been well investigated for use in Ghana with regards to analyzing extreme rainfall events. This study therefore seeks to examine the role that meridional winds play in generating extreme rainfall events over Accra.

According to de Boer et al. (2008), meridional wind flow causes overturning in the Atlantic Ocean and are the main features of the global overturning circulation which give rise to massive cloud developments. The ocean would therefore not support deep convection if there were no winds or vertical diffusivity that are high enough to initiate overturning in the atmosphere. There had been suggestions that the fluctuations in the Southern Hemisphere winds can change the pathways of the Atlantic meridional overturning circulation as well as the properties of the water and the associated heat and transportation of freshwater (Speich et al., 2007). Wind patterns have changed recently over southern Ghana due to climate change (Asante & Amuakwa-Mensah, 2015). There is therefore the need to study the recent wind patterns that initiate perturbations for atmospheric overturning to take place along the coast of Ghana.

3 Data and Methods

Rainfall and meridional wind data for 40-year, 1980-2019, have been chosen for this study and centering on the year 2000 to find out how climate change has affected extreme rainfall events over Accra. The year 2000 has been used in this study as a baseline to divide two perceived climatic regimes based on observations, similarly as applied by some previous studies for examining a possible shift in rainfall trends in the West African region (Owusu et al., 2008; Owusu & Waylen, 2009, 2013). This is based on the fact that from the year 2000, the frequency of extreme rainfalls was observed to have increased. Consequently, for our study, two epochs are defined; 1980-1999 and 2000-2019, to enable us to examine the changes in the rainfall and wind patterns on either side of the year 2000.

3.1 Study area

The study area for this work is Accra, the capital city of Ghana. It is located along the Guinea Coast of West Africa, approximately between 0.3ºW to 0.1ºW and 5.5ºN to 5.7ºN, at an approximate altitude of 68 m above mean sea-level (Figure 1). However, a wider area covering 3.0ºW to 3.0ºE and 0.0º to 8.0ºN, which forms part of southern Ghana has also been considered.

In our analyses, there are also instances where a much larger area, comprising of the North and South Atlantic Oceans as well as portions of the western parts of the Indian Ocean are considered for their teleconnection impacts on western Africa. The coast of Ghana can be divided into three geographical zones, the Western, Central, and the Eastern coasts. The Western coastline is about 95 km long and ends at the border with Cote d'Ivoire while the Central Coast is about 321 km. The Eastern coast, where Accra belongs, is about 149 km (Boateng et al., 2017) and ends at the border with the Republic of Togo. The study area is urbanized and also noted for commercial fishing activities at the local, coastal communities. Accra is a low-lying coastal city and is mostly affected by flooding whenever it rains heavily (Appeaning-Addo, 2013; Owusu & Obour, 2021).

The Gulf of Guinea, which is located to the south of the country has been the main source of moisture supply for massive cloud developments and rain formation over Ghana. For this reason, it has become interesting to investigate wind components at the atmospheric boundary layer (i.e., 850 hPa level). This is to examine how these winds influence the moisture content of the airmass that affects the coast of Ghana and generate extreme rainfall occurrences.

3.2 Data

In this study, we used quality-controlled homogeneous daily rainfall data collected with rain gauge from the Ghana Meteorological Agency (GMet) sampling station at the Kotoka International Airport Meteorological Office (KIAMO), Accra, Ghana. The data covered the period 1980-2019.

Daily 2.5°×2.5° gridded 850 hPa meridional wind, as well as surface temperature reanalysis data were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Prediction (Kalnay et al., 1996). Top of Atmosphere (TOA) brightness temperature data on a 0.07°×0.07° grid, used as a proxy to track storms in the study area, were obtained from NOAA National Centers for Environmental Information (Knapp, 2008).

3.3 Methods

In this study, we defined extreme rainfall events as done in Seleshi & Camberlin (2006) and Krishnamurthy et al. (2009); days with rainfall equal to or exceeding the 1980-2019 95th percentile (i.e. 44.40 mm). Effectively, only days with rainfall in the top 5% of all days with rainfall (i.e. 142 days) are considered. We examine two components of the extreme events; (a) frequency, defined as the number of days with extreme rainfall events and (b) intensity, defined as the daily mean of extreme rainfall events. A test of significance between the rainfall and meridional winds has been investigated using student's *t*-test. The *t*-test has been used to compare the two climatic means, those of the pre-2000s and the post-2000s to study the differences that exist between their rainfall distributions. The mean ($\bar{X}$) is given by the formula, $\bar{X} = \frac{\sum x_i}{n}$, where *n* is the number of samples and x_i is the n^{th} term of the distribution. The sample standard deviation (σ_s) is estimated with equation 1 (Eq.1) with a degree of freedom, *df*= *n*-1. The *t*-statistic is thus computed using Eq.2.

$$\sigma_s = \sqrt{\frac{\sum (Xi - \bar{X})^2}{\mathrm{n-1}}}, \qquad (1)$$

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{(n_1-1)\sigma_1^2 + (n_2-1)\sigma_2^2}{n_1 + n_2 - 2}} \text{ x } \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}. \quad (2)$$

The *p*-value is used to examine the statistical significance of the differences between the parameters during the two climatic periods examined.

4 Results and Discussions

The amount of rainfall over Accra has generally recorded an increasing trend since 1980 (Figure 2). Rainfalls have been generally higher during post-2000 than they were during pre-2000 (Table 1). The *t*-test conducted at 95% confidence level between the two climatic periods indicates that all the respective months had *p*-values higher than 0.05, suggesting that the difference in monthly total rainfall between pre-2000 and post-2000 for Accra is not statistically different. Nevertheless, the overall results show that the month of the most intense rainfall events has shifted from July during the pre-2000 era to June during the post-2000 era (Figure 3a). The mean rainfall had been higher for June during post-2000 than pre-2000. Although January had the most intense rainfall event (112.5 mm) during post-2000, this was a one-time event and could be considered an anomaly (Figure 3). The shift in rainfall patterns in general can lead to crop failures. Additionally, it affects water resource sharing in the region as well as operation of infrastructure such as dams, which contribute to hydro-electric generation and irrigation. Thus, information on the variability (shift) in extreme rainfall is essential for use in planning towards the risks as well as the opportunities associated with such climate hazards.

The frequency of extreme rainfall events in the post-2000 was higher than in the pre-2000 (Figure 3b). Notably, there have been more extreme rainfall events during post-2000 winter than pre-2000 winter. For example, there were respectively 3, 1, and 6 extreme rainfall events during December, January and February of post-2000 compared to none during December and January and 1 during February of pre-2000 (Figure 3b). Consequently, mortalities associated with extreme rainfall have also increased during the post-2000 over Accra than the pre-2000 with the increased mortalities (Table 2) also aided by land surface changes, human behaviors, and congestions (Emmanuel, 2018; UN DHA, 1995).

There had also been differences in the meridional wind pattern at the 850 hPa level between the two climatic periods for all the months, with *p*-values lower than 0.05, except for June, July, and August which had the *p*-values of more than 0.05 between the pre-2000 and the post-2000 (Table 3). Northerly winds (negative meridional winds) were stronger during the pre-2000 than the post-2000 whilst southerly winds (positive meridional winds) were stronger during the post-2000 than the pre-2000 (Table 3).

4.1 Temperature changes

Monthly mean surface temperature distribution over southern Ghana has been estimated to have a mean value of 26 ^{o}C for the study period, 1980 to 2019 (Figure 4a). However, a trendline indicates that the pre-2000 surface temperature was below the average while the post-2000 surface temperature was above the average. This suggests a possible effect of climate change and warming over southern Ghana. Comparing temperatures of both periods, the pre-2000 had most of its months with mean temperatures below 26 ^{o}C while the post-2000 period only had fewer months below this value. The trend in observed temperatures over the periods positively agrees with the trend in meridional winds at the 850 hPa level (Figure 4a and 4b). This suggests the influence of changing temperatures on meridional winds, which in turn affects rainfall distribution pattern and intensity in the region. Studies have shown positive relationships between temperature and meridional winds.

4.2 Meridional Wind changes

Monthly mean meridional winds at the 850 hPa level during the pre-2000 period were dominated by strong northerly winds while the post-2000 period was dominated by strong southerly winds (Figure 4b). This suggests that the northerly winds became gradually weakened during the late 1990s and southerly winds started to become stronger during the early 2000s. The strongest mean monthly meridional wind recorded in the pre-2000 was a northerly wind with a speed of 3.6 m/s in January 1983 (Figure 4b). That year experienced the poorest annual rainfall in the history of Accra (Figure 2). Conversely, the strongest mean monthly meridional wind in the post-2000 was southerly with a speed of 2.7 m/s, recorded in May 2008 and 2019 (Figure 4b). Notably, the year 2008 recorded the highest annual rainfall in Accra during the study period (Figure 2). There had been no month in the pre-2000 with a mean southerly wind of more than 2.0 m/s whilst there had also not been a month in the post-2000 with a northerly mean wind speed of up to 2.0 m/s (Figure 4b).

Changes in the pattern of meridional winds along the Gulf of Guinea coast affects the position of the intertropical convergence zone (ITCZ), thus affecting the distribution of rain. According to (Nicholson & Grist, 2003), the ITCZ lies between the transition between the northerly wind and the southerly wind and migrates from around latitude 9 ºN in January and 20 ºN in August. The location of this ITCZ is a position on the surface of the earth where maximum heating and convective activities take place, therefore, rainfall is usually abundant and torent.

4.3 Pre-2000 extreme rainfalls over Accra

The highest rainfall during the pre-2000 over Accra is observed to occur on 3rd July 1995 with an amount of 243.9 mm (Figure not shown). Satellite information on meridional winds at the 850 hPa level on that 3rd July 1995 indicated strong southerly winds of about 9 m/s over the South Atlantic Ocean (Figure 5a). This wind strength had the potential to transport enough moisture from the sea towards the coast of Ghana. They however weakened as they approached the coast of Ghana to deposit their moisture content as rain. An opposing northerly wind, therefore, prevailed over the Sahel with about the same strength, 9 m/s and weakened to about 2 m/s as they reached the coastal sector of Ghana (Figure 5 a). This created a wind convergence zone. The maritime winds were restricted from moving further inland into the West African sub-region by the opposing continental winds. The two air masses mixed and was lifted for massive condensation to occur and form massive clouds. The storm that was created by this scenario stagnated over the Gulf of Guinea Coast and produced heavy rainfall for a long period. Satellite imageries indicated that the storm stayed over the whole country for more than 12 hours (Figure 5).

This storm was sighted on satellite over Nigeria at 1130 UTC on 3rd July 1995 (Figure 5b) propagating westward, and six hours later it was located over the eastern half of Ghana. As at 2330 UTC, the storm occupied almost the whole of Ghana (Figure 5c) and start to exit the country into

La Cote d’Ivoire around 0530 UTC the following day, on 4th July 1995 (Figure 5d). This particular storm is quite spectacular; it developed an “eye-like” structure, a phenomenon usually associated with tropical cyclones, which is very rare over the West African sub-region. The “eye” can be visible at 1130 UTC when it was over Nigeria (Figure 5b) and also when it was exiting Ghana into Cote d’Ivoire at 0530 UTC on 4th July 1995 (Figure 5d). It took the storm about 6 hours to propagate from the western borders of Nigeria to Ghana and stayed over Ghana for about 12 hours. The shape of the storm has a spiral nature which led to the development of the “eye-like” structure and the stagnation.

In 1983, the lowest extreme monthly rainfall in the pre-2000 over Accra was recorded with an amount of 46.3 mm. Meanwhile, it has also been the year with the poorest record of rainfall in Accra during the study period (Figure 2). That highest amount of rain for that year was recorded on the 19th of June (Figure not shown). From NOAA satellite information, the entire country was occupied by northerly meridional winds at the 850 hPa level as well as over the South Atlantic Ocean, the moisture source for West Africa (Figure 6a). Strong northerly winds of up to 10 m/s were observed over the South Atlantic Ocean with just a few portions experiencing weak ‘pockets’ of southerly winds. The Sahel was therefore dominated by strong northerlies up to 6 m/s which brought drier winds to Ghana and made it impossible to sustain massive cloud developments. Considering annual total rainfall amounts, the year 1983 was associated with the lowest rainfall, dry spells, drought, and very hot weather conditions with famine in Ghana (Tan & Rockmore, 2019). A weak storm was spotted on the Meteosat-2 IR satellite imagery on the 20th June 1983 at around 0530 UTC which produced this highest rainfall for the year. The storm, though propagated from the east of the country to the west, the center was slightly north of the coastline (Figure 6b).

4.4 Post-2000 extreme rainfall over Accra

The highest rainfall event in the post-2000 occurred on June 3, 2015, over Accra, with a recorded amount of 212.8 mm. Satellite information from NOAA indicated that strong southerly meridional winds of about 15 m/s were observed over the South Atlantic Ocean and as they approached the coast of Ghana, they weakened to about 3 m/s (Figure 7a). This is an indication of sufficient moisture transport from the Atlantic to the coast of West Africa. As at 0900 UTC on the 3rd of June 2015, a storm developed just along the coastline, stretching from the west of Nigeria to Togo and moved westward. Three hours later, the storm entered Ghana over the southeast and started raining heavily (Figure 7).

The lowest extreme rainfall for the post-2000 was recorded on 24th June 2012 with an amount of 47.9 mm. At that time, satellite information from NOAA indicated that though southerly winds prevailed over the south Atlantic Ocean, the speeds were not strong, about 6 m/s, with a large ‘pool’ of strong northerly winds prevailing over the Gulf of Guinea and extending far into North Africa (Figure 8a). For this reason, the convergence zone between the southerlies and the northerlies occurs offshore, far away over the sea. As a result, massive cloudiness did not occur close to the land, the northerly winds, therefore, prevented sufficient moisture from reaching the coast of West Africa. Nonetheless, on the 24th of June 2012, the highest rainfall amount of the year was recorded from a weak storm cell that tracked across the inland areas of the country with a small storm cell surviving along the coast (Figure 8b).

From the results, both southerly winds and northerly winds at the 850 hPa level have their peculiar ways of influencing extreme rainfalls over Accra. When strong southerly winds over the South Atlantic Ocean become weak as they approach the coast of West Africa, they produce excessive rains over Accra. Conversely, when strong northerly winds affect the coast of West Africa without becoming weak, they reduce rainfall amounts over Accra. It has also been noted that if the southerly winds are too strong over southern Ghana, most of the moisture tends to be transported further inland, leaving the coast with little amounts of rain. The highest monthly total rainfall amounts for both periods were recorded in June (Table 1) with southerly wind speeds of 0.6 m/s and 0.9 m/s during 1980-1999 and 2000-2019 respectively (Table 3). This implies that for the post-2000 era when meridional winds are southerly along the coast of Ghana with speeds around 0.9 m/s they are capable of producing intensive rainfall.

Because Accra is located along the coast, when southerly winds are very strong, they tend to drive moisture further away into the inland, depriving the coast from heavy rains. When southerly winds are weak as they approach the coast of West Africa, they tend to dampen moisture along the coast and help to form massive clouds that produce heavy rains. Similarly, when northerly winds are very strong, they tend to bring in dry air from the land or drive away the available moisture further into the Gulf of Guinea leaving the coast dry. However, if the northerly winds become weak as they approach the coast, they tend to serve as a blockade to prevent moisture from the ocean from leaving the coast further inland.

5 Conclusion

The frequency, intensity and variability of rainfall are important to the socio-economic livelihood of many across the globe. Extreme rainfall can be devasting, causing loss of lives and damages to properties. In this study, we investigated the recent changes in extreme rainfall over Accra using rain gauge and satellite-derived data. The study covered 1980-2019 and was divided into two epochs; 1980-1999 and 2000-2019. Our results suggest that possible climate change has affected the monthly rainfall distribution for June, such that post-2000 June rainfall totals are higher than the pre-2000. During the pre-2000 era, the most intense rainfalls occurred during July. This shift is important for planning purposes to help mitigate against the associated negative impacts. Even though mean monthly meridional winds at the 850 hPa level were southerly for both the post-2000 and the pre-2000 for June, the values were higher during the post-2000 than those of the pre-2000 (Table 3). The findings show that both southerly winds and northerly winds at the 850 hPa level have forecast potential and can be used in addition to other parameters to predict extreme rainfall events over the study area. It is therefore recommended that further studies be done on how meridional winds at the surface influence and affect the weather conditions along the coastal sector of Ghana.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Availability of data and materials

Rainfall data were collected from the Kotoka International Meteorological Office (KIAMO) in Accra by the Ghana Meteorological Agency, https://www.meteo.gov.gh/gmet/. Meridional winds at 850 hPa pressure level and surface temperature data were obtained from the National Oceanic and Atmospheric Administration (NOAA) NCEP Reanalysis Derived data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at https://psl.noaa.gov/data/timeseries/

Code Availability

None

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Figures

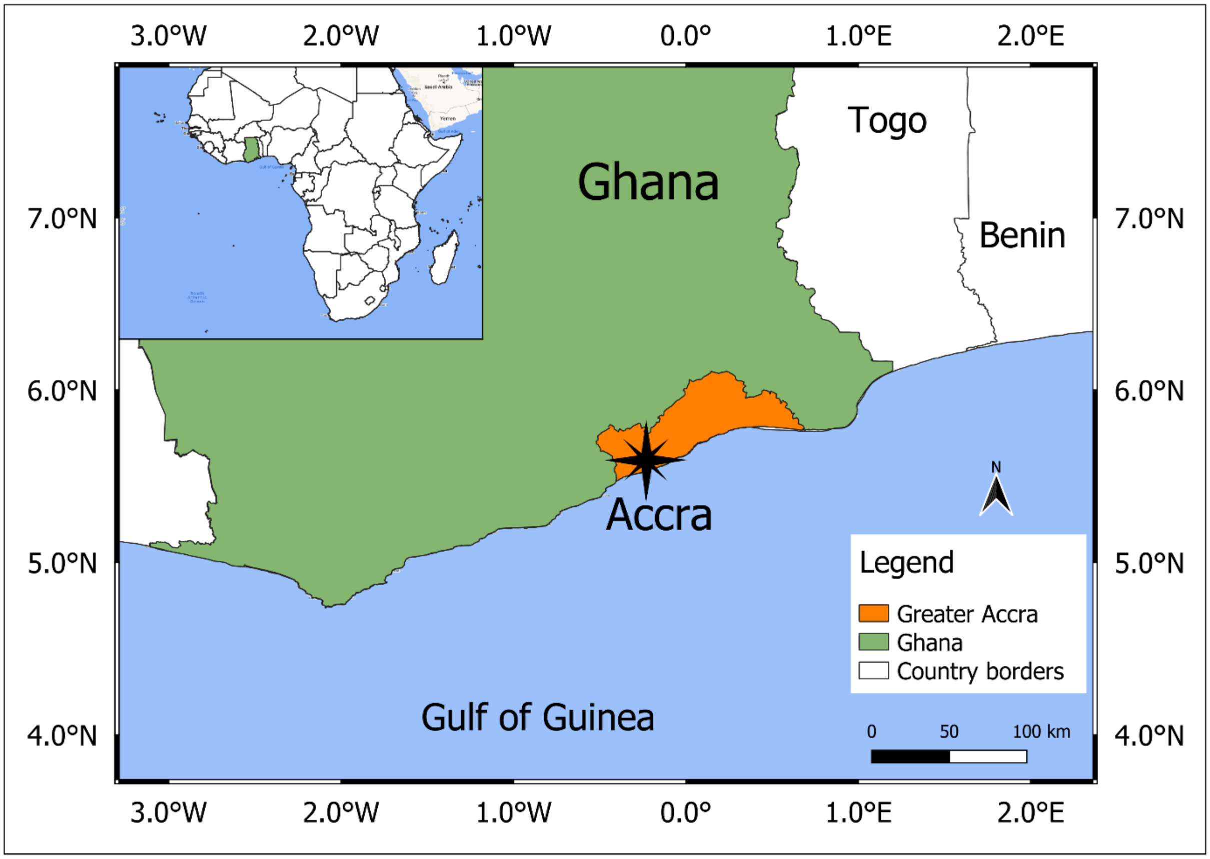

Figure 1. Map of Ghana and Accra, showing the study area.

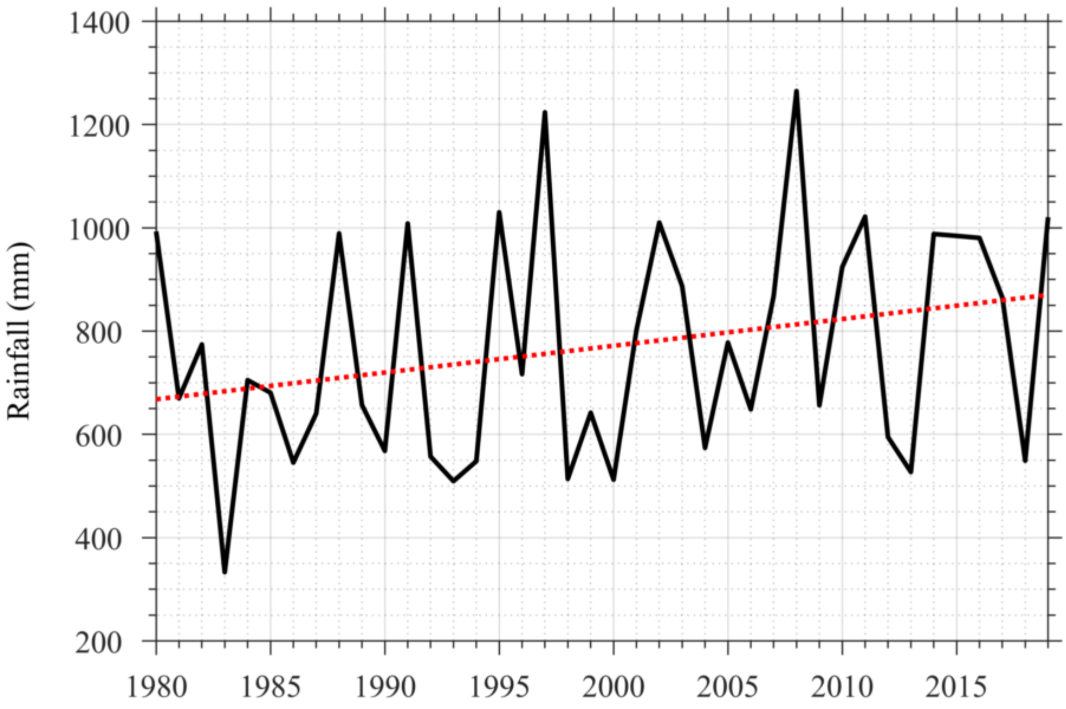

Figure 2. Annual rainfall totals (mm) for Accra.

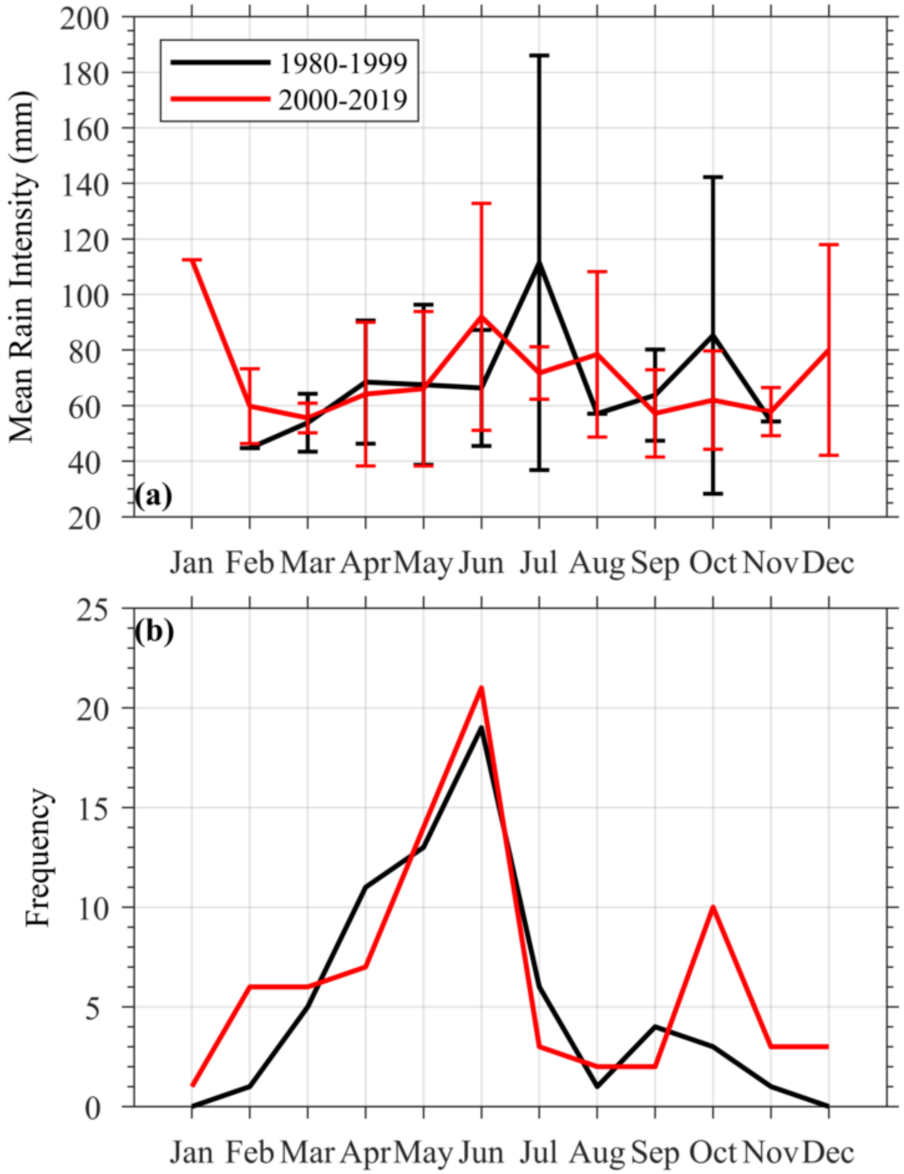

Figure 3. (a) Monthly mean rainfall intensity, and standard deviation (mm) and (b) monthly frequency of extreme rain events over Accra during pre-2000 (black line) and post-2000 (red line).

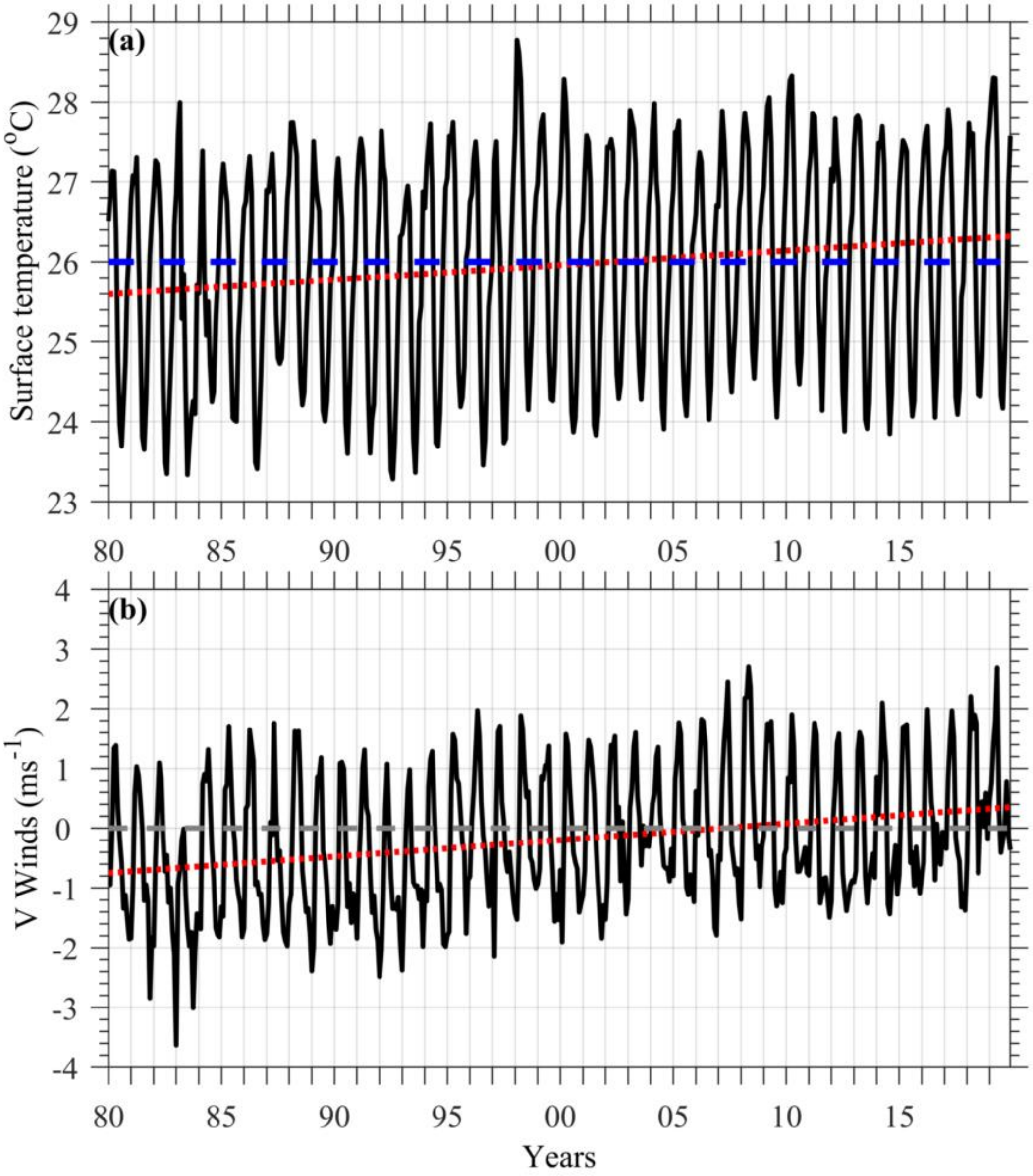

Figure 4. Monthly mean (a) surface temperature (^{o}C) and (b) meridional winds (ms^{-1}) over southern Ghana. Dashed red lines show linear trend. Dashed blue line in (a) marks the mean surface temperature (i.e., 26 ^{o}C).

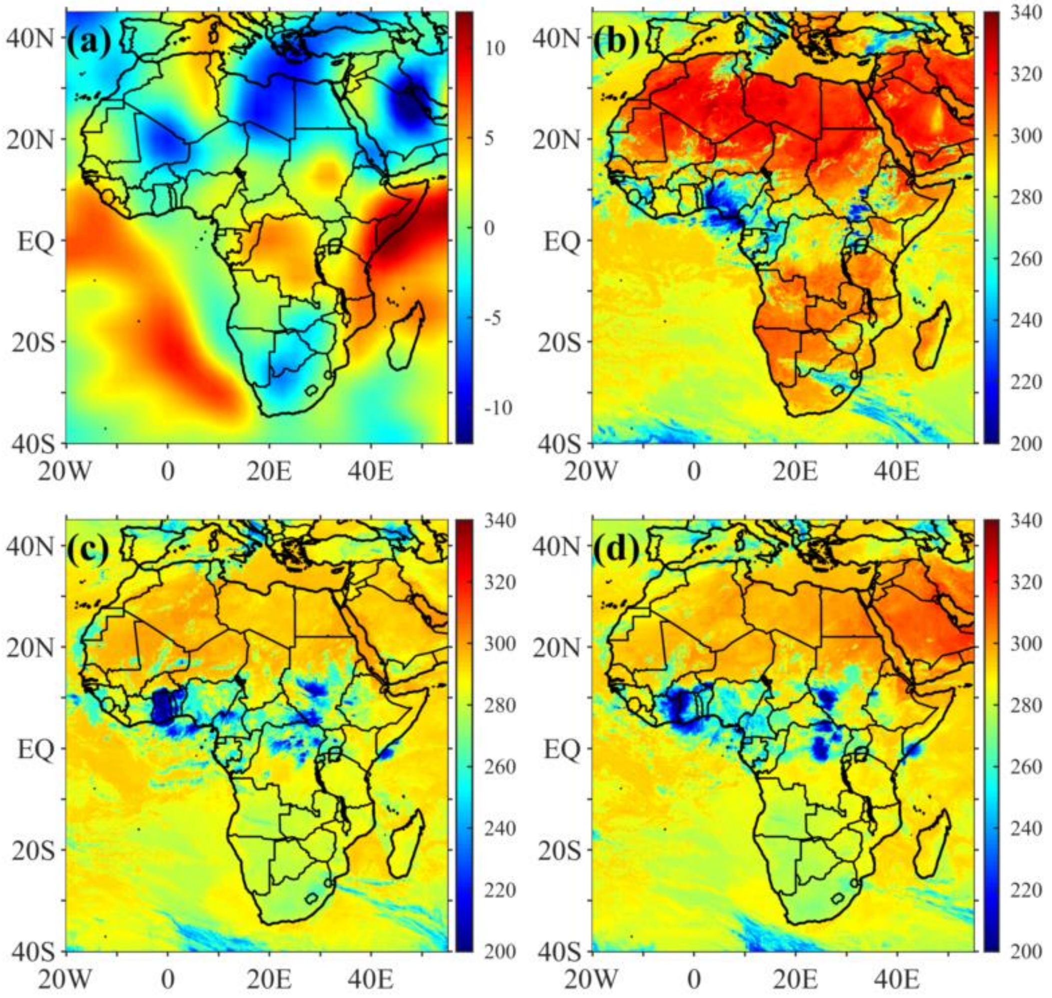

Figure 5. (a) 850 hPa meridional winds (ms^{-1}) averaged for 2-3 July 1995; (b) Top of Atmosphere (TOA) brightness temperature (K) at 1130 UTC on 3 July 1995, (c) at 2330 UTC on 3 July 1995, and (d) at 0530 UTC on 4 July 1995.

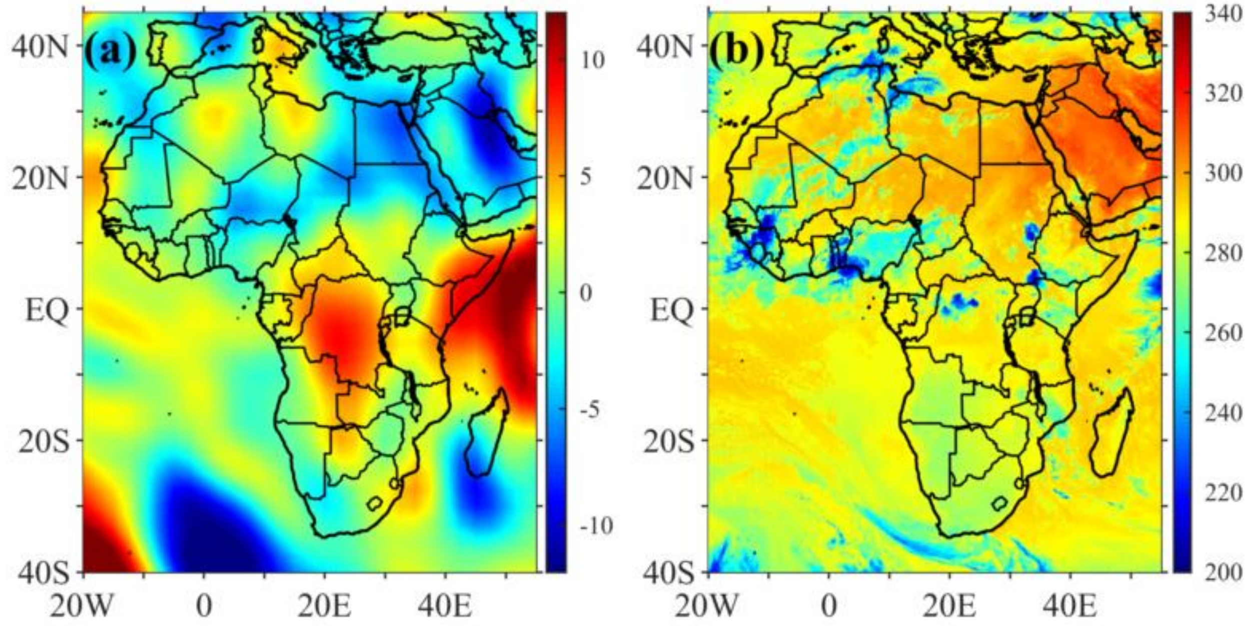

Figure 6. (a) 850 hPa meridional winds (ms^{-1}) averaged for 18-19 June 1983; (b) TOA brightness temperature (K) at 0530 UTC on 20 June 1983.

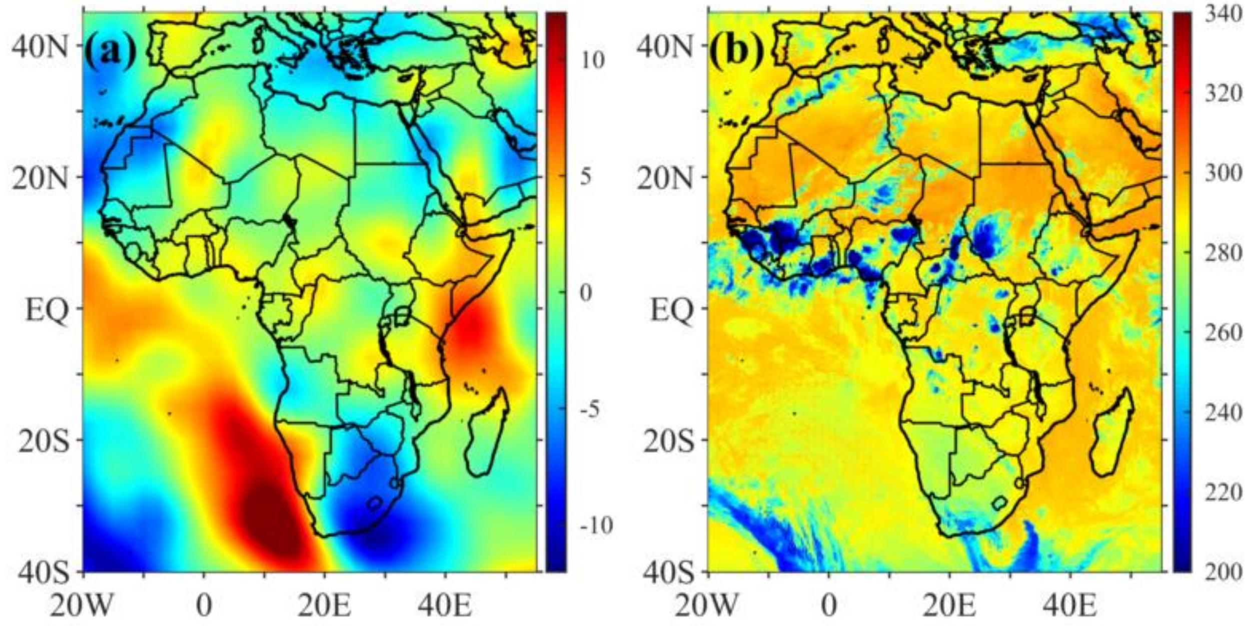

Figure 7. (a) 850 hPa meridional winds (ms^{-1}) averaged for 2-3 June 2015; (b) TOA brightness temperature (K) at 2100 UTC on 3 June 2015.

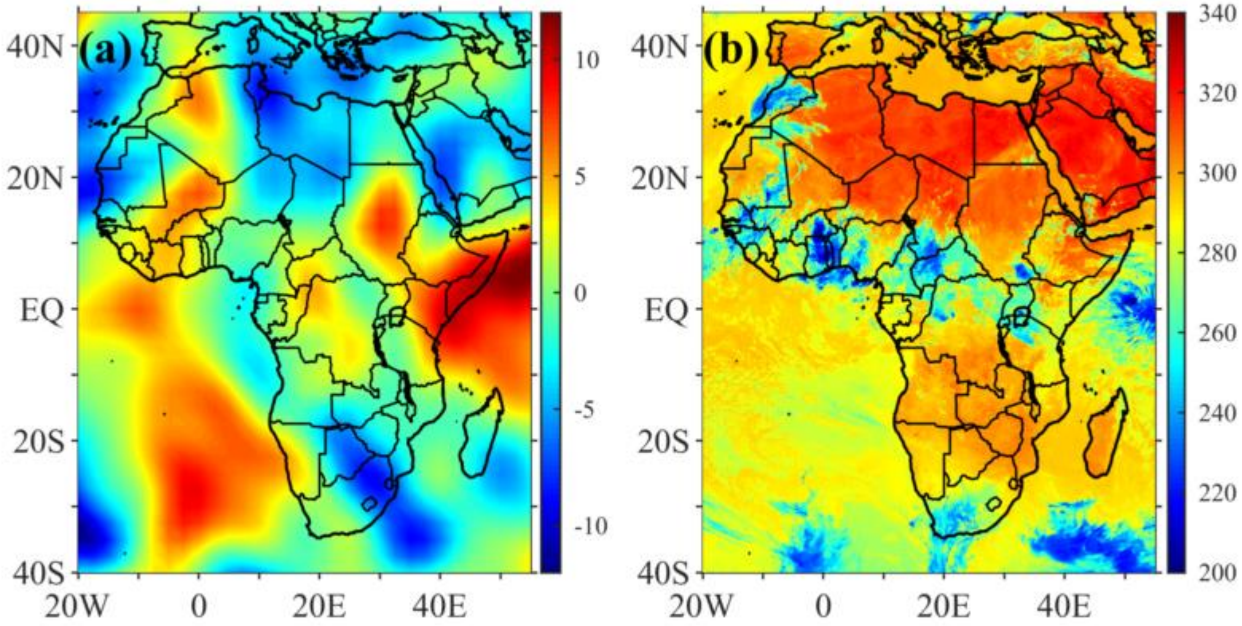

Figure 8. (a) 850 hPa meridional winds (ms^{-1}) averaged for 23-24 June 2012; (b) TOA brightness temperature (K) at 0900 UTC on 24 June 2012.

Tables

Table 1. Mean, standard deviation, and the p-values for t-test of the monthly rainfall totals (mm) in Accra for the pre-2000 and post-2000.

Monthly Rainfall Totals over Accra

Months	Mean [mm]		Standard Deviation [mm]	
	1980-1999	2000-2019	1980-1999	2000-2019
Jan	5.3	15.4	7.3	26.3
Feb	13.0	31.0	18.1	43.1
Mar	54.9	59.2	48.4	48.5
Apr	84.7	85.4	65.9	56.8
May	146.8	153.0	70.4	80.0
Jun	158.3	196.2	94.2	91.1
Jul	67.6	54.0	74.1	37.3
Aug	23.9	23.6	26.1	26.9
Sep	49.4	52.1	62.2	32.7
Oct	65.9	84.8	47.3	54.5
Nov	27.7	36.4	22.6	29.7
Dec	17.6	33.6	24.5	37.3

Table 2. Effects of reported extreme rainfall occurrence in Accra pre- and post-2000 (Osei-Tutu, 2020).

Date of extreme rain	**Effect/impact**	**Period**
July 5, 1995	Storm caused flooding in low areas in the Accra metropolis; commuters and vehicles and electric substation were affected and resulted in power cuts.	Pre-2000
June 13, 1997	Hours of an intermittent downpour for two continuous days in Accra caused floods.	Pre-2000
June 28, 2001	Over 300,000 people affected in an early morning downpour that submerged portions of the city.	Post-2000
May 5, 2010	Central Accra and other areas deeply submerged in water after two hours of stormy rains.	Post-2000
June 22, 2010	Death toll of 35 recorded after one of the nation's worst flood disasters.	Post-2000
February 24, 2011	A downpour wreaked extensive havoc on properties in most parts of Accra and some of its surrounding communities.	Post-2000
November 1, 2011	43,087 people affected, with 14 deaths recorded after a downpour occurred in Accra.	Post-2000
May 31, 2013	Heavy rains caused flooding in many parts of Accra.	Post-2000
June 3, 2015	Over 160 lives lost with property after a heavy downpour in Accra caused flooding, triggering a fuel station explosion.	Post-2000

Table 3. Mean, standard deviation, and the p-values for t-test of the mean monthly meridional winds (ms^{-1}) at the 850 hPa level for southern Ghana for the pre-2000 and post-2000.

Monthly Meridional Winds Over Southern Ghana

Months	Mean [m/s] 1980-1999	 2000-2019	Standard Deviation [m/s] 1980-1999	 2000-2019	*p*-value *t*-Test
Jan	-1.66025	-0.56085	0.727699	0.667922	0.00001447
Feb	-1.17115	0.02745	0.665026	0.755117	0.000004966
Mar	0.14685	1.08375	0.594539	0.57255	0.0000105
Apr	1.02225	1.65730	0.554261	0.260709	0.00008076
May	1.23060	1.69675	0.45064	0.396349	0.001315
Jun	0.60775	0.90605	0.678951	0.725613	0.1874
Jul	-0.09870	-0.22305	0.726778	0.682128	0.5802
Aug	-0.63430	-0.58645	0.59137	0.51057	0.7857
Sep	-0.97085	-0.61615	0.356568	0.464909	0.01035
Oct	-1.25130	-0.57015	0.56598	0.500674	0.0002621
Nov	-1.53590	-0.78105	0.491086	0.57316	0.00007056
Dec	-1.61855	-0.89095	0.382913	0.513702	0.00001253