Precipitation Trends and Patterns across Sub-Saharan Latitudes: A Meridional Assessment of Frontal and Convectional Rainfall in Cameroon

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ABSTRACT

This study investigates current rainfall trends and the ecological significance of frontal and convectional rains in Sub-Saharan Africa, focusing on Cameroon. By utilizing satellite data and ground station records, it provides a comparative meridional analysis from Kribi in the south to Maroua in the north. The research applies statistical tools such as the Mann-Kendall trend test, coefficient of variation, and Precipitation Concentration Index to assess rainfall variability and intensity. Results indicate an increasing rainfall trend from northern to southern Cameroon and reveal moderate to irregular distribution patterns. These findings highlight the critical need for adaptive strategies in agriculture and water management to enhance resilience against climate variability.

Keywords: Rainfall dynamics, frontal rains, convectional rains, Cameroon, climate variability

INTRODUCTION

An Overview of Rainfall, Rainfall Measurement and Water Resources: Frontal and Convectional Rains

Rainfall is a critical component of the earth's hydrological cycle, playing a vital role in replenishing freshwater resources, supporting ecosystems, and influencing weather patterns, and so understanding how it forms is essential for comprehending broader climatic systems and their impact on human activities (Apchu et al, 2015). Rainfall, the most prominent form of precipitation, forms particularly by condensation in the atmosphere, where the hygroscopic water droplets usually would not outweigh the force of rising air currents and thermals which initially caused their condensation, until they are way more than 0.05 mm in diameter (David Waugh, 2005). These rain droplets grow in diameter mainly due to their collision and coalescence with each other, and the sheer addition of freshly condensed water and ice crystals, the latter which directly contributes to their growth in size.

A closer examination of this formation process will reveal it to be formed when saturated air (air that cools at dew point) is heated and rises either by a mountain, conventional currents or frontal action (Gbetibouo et al, 2010). The rising saturated air or water vapour cools as it rises. It attaches itself to tiny particles of dust, salts, seeds or smoke in the atmosphere (David Waugh, 2005). These particles are commonly called condensation nuclei. Condensation takes place when the water droplets join together on the condensation nuclei to form raindrops. Clouds are formed as the rain drops develop. As the cloud develops further, they become heavy and unstable, but cools at the dry adiabatic rate. This adiabatic rate means that for every 1,000 metres rise, the temperature of the water droplets reduces by 10^{o}C (Gbetibouo et al, 2010). Precipitation or rainfall comes to the ground when about 300 metres above the earth's surface, the cloud rises further. The rising clouds become warmer than the surrounding air, making it unstable. As it develops further, it becomes very heavy and falls to the ground as rain. The type of rain that falls depends on the factors responsible for rising of the saturated air. Each type of rainfall requires a different mechanism that triggers the vertical movement of unstable air. The amount of rainfall recorded at a place is measured by an instrument called Rain Gauge. Rain Gauge is a copper cylinder with a collection Jar inside and a funnel on top. The gauge is placed into the ground leaving only 30 cm of the top above the ground level to prevent splashing water from entering it. Rain falls through the funnel on top of the copper cylinder and is collected into the jar. The water is collected after 24 hours, and then poured into a measuring cylinder for measurement to be taken (Apchu et al, 2015).

Rainfall plays a significant role in the management of water supplies. Determination of areal rainfall of a catchment, for example, is the prerequisite for various water resource and watershed modeling studies (Bayraktar et al. 2005; Cheng et al. 2012). The average rainfall is usually used to calculate the spatial rainfall status of a region and its input into various rainfall–runoff models (Ayoad 1983; Belay et al. 2019). So, rainfall analysis is considered imperative in hydrology and in climatological studies that are used to identify its characteristics, duration, and variability in terms of temporal and spatial distribution (Gummadi et al. 2018).

Rainfall and river flows in sub-Saharan Africa display high levels of variability across a range of spatial and temporal scales, with important consequences for the management of water resource systems (Sutcliffe and Knott 1987; Grove 1996; Laraque et al. 2001; Conway 2002; Ogutunde et al. 2006; Hamandawana 2007). Throughout sub-Saharan Africa, this variability brings significant implications for society and causes widespread acute human suffering and economic damage. Examples of variability include prolonged periods of high flows for rivers draining large parts of East and sub-Saharan Africa (Conway 2002), and multidecadal anomalies in river flow regimes in parts of West Africa where long-term mean yields of freshwater into the Atlantic Ocean fell by 18% between 1951–70 and 1971–89 (Mahe´ and Olivry 1999). There are many examples of the challenges posed by water resources variability in Africa: Lake Chad fisheries (Sarch and Allison 2000), reservoir management on the Senegal River (Magistro and Lo 2001), balancing supply and demand for Nile water in Egypt (Conway 2005), irrigation management in the Greater Ruaha River in Tanzania (Lankford and Beale 2007), and hydropower generation in the Kafue (Sutcliffe and Knott 1987) and Lake Victoria basins (Tate et al. 2004). As anthropogenic climate change becomes increasingly manifest, the prospect of shifts in flows and variability underscores the need for better understanding of the drivers of variability and rainfall–runoff interactions. It is likely that extreme events are going to be the greatest socioeconomic challenge. Although sub-Saharan Africa is generally associated with drought-related influences, anecdotally there appears to be greater frequency and spatial extent of damaging floods, particularly in East and sub-Saharan Africa (for example, during 2006 and 2007). Extreme floods have caused substantial socioeconomic disruption in Mozambique (2000; Christie and Hanlon 2001) and East Africa (1961, 1978, and 1997; Conway 2002), whereas smaller floods may be somewhat overlooked but locally significant, for example, in Nigeria (Tarhule, 2005). Late 2006–07 saw major floods of unprecedented spatial extent (and timing) sub-Saharan and parts of East Africa, which is broadly in line with projections in the Intergovernmental Panel on Climate Change's Fourth Assessment Report for increases in autumn and winter rainfall (Christensen et al. 2007).

The distribution of rainfall is not uniform due to regional orographic effects and sources of rain. Thus, sub-Saharan Africa receives rainfall in two main seasons (double maxima), with locations farther away from the equator receiving it in one (single maxima). The main rainy seasons known as Summer (June–October/November) is the long rainy season; the second is the short rainy season in Spring (February and March (Aldabadh et al., 1982; NMSA 1996; Seleshi & Zanke 2004; Cheung et al. 2008). Rainfall variability is an important feature of both semi-arid and equatorial climates, and climate change is likely to increase this variability. Generally in the sub-Saharan region, climate change is likely to increase rainfall variability with summer seasonal rainfall comprising the largest share (Al-Houri 2014; Girma et al., 2019). Inter-seasonal rainfall variation and intra-annual rainfall availability, as well as reliability, significantly affect agricultural activities, hydrologic conditions, and livelihoods (Ramos & Martínez-Casasnovas, 2006; Hessebo et al., 2019). There is high intra-annual variability of rainfall in most parts of of sub-Sahara (Seleshi & Zanke, 2004; Mengistu et al. 2014). The variability of monthly and seasonal rainfall is higher than that of annual rainfall (Aldabadh et al., 1982; Seleshi & Zanke, 2004; Ngongondo et al., 2011). Rainfall fluctuation occurs both in annual variability and interannual variability (Eshetu et al. 2016). This is because rainfall occurrence in the region at various gauging stations has been found to vary significantly, contingent on source of rain and regional landscape (Singh 1992). The point rainfall data are recorded using the installed gauging stations (Sen & Habib 2000). This point rainfall data are converted to areal rainfall data that represent the quantity of rainfall that falls on the region. Hence, areal rainfall estimations are very sensitive to the number and locations of rain gauges (Wilson 1970; Bell & Moore 2000; Ngongondo et al., 2011; Cho et al. 2017; Kadhim et al., 2020). Moreover, the average annual rainfall depends on the elevation and tends to increase with increasing elevation (Faures et al., 1995; Hessebo et al., 2019). The other biophysical factors also affect rainfall and result in marked spatiotemporal variability at small distances (Oettli & Camberlin, 2005; Terink et al. 2018). This relative difference in between rain gauges was determined as one more feature related to their biophysical factors (Nyssen et al. 2005; Bewket & Conway 2007; Taesombat & Sriwongsitanon, 2009; Ngongondo et al., 2011; Nandargi & Mulye, 2012; Zhang et al. 2016). The aforementioned studies indicate that spatiotemporal rainfall variability affects the rainfall occurrence and distribution in various regions. In reply to the increasing worry about rainfall studies, investigators have started to improve techniques of evaluating the rainfall distribution and intensities. Researchers calculate the amount of rain that falls on the station, by converting it from point rainfall data to represent the quantities that fall on the region as a whole and not on the station itself (Yuan et al. 2014). This is represented as the areal rainfall of the region. So far, several kinds of areal rainfall estimation methods have emerged (Cheng et al. 2012; Eruola et al., 2015; Cho et al. 2017; Kadhim et al., 2020) such as: Arithmetic Mean, Statistical, Isoheytes, and Thiessen methods, but no method accurately represents rainfall distribution (Sen & Habib 2000).

For condensation and precipitation to occur there must be an appreciable ascent of an air mass. Since this ascent is brought about in three ways, there are three main types of rainfall. These are: Conventional Rainfall Orographic or Relief Rainfall and Frontal or Cyclonic Rainfall. Each of these types of rainfall is characterized with its features and their diagrams are different from each other. Below are the types and the characteristic features associated with them (Apchu et al, 2015).

REVIEW OF EXISTING RESEARCH ON FRONTAL AND CONVECTIONAL RAINS

Frontal Rainfall

Frontal, convergent or cyclonic rainfall occurs when two air masses of separate temperatures and humidity levels meet. This phenomenon is particularly significant in meteorology, as it plays a crucial role in the distribution of rainfall across various geographical regions, including sub-Saharan Africa. The dynamics of frontal rainfall are primarily governed by the interactions between warm and cold air masses, which can lead to the formation of weather fronts (Zikhali et als, 2010). When a warm maritime air mass (lighter) meets a cold air mass (heavier), the warm air mass is under-cut by the cold air mass. The warm air mass is forced to rise because it is lighter. The warm water vapor cools down as it rises. The rising air condenses or condensation takes place, and clouds are formed on the condensation nuclei (particles in the air) in the atmosphere. As the clouds rise further they become unstable due to more water droplets accumulating. They fall to the ground as cyclonic rainfall (Apchu et al., 2015).

Frontal rains typically occur along weather front, which are boundaries separating different air masses (Minghu Cheng, 2000). This front or point of air convergence is the Intertropical Convergence Zone (ITCZ), also called the tropical discontinuity, which, as its name suggests, is limited to within the Tropics of Cancer and Capricorn (Waugh, 2005). Three main types of fronts associated with precipitation exist: *cold fronts*, *warm fronts*, and *occluded fronts* (Minghu Cheng, 2000).

- *Cold fronts* occur when a colder, denser air mass pushes into a warmer air mass. The warm air is forced to rise rapidly, leading to cooling and condensation. This process can result in the development of cumulonimbus clouds and often leads to heavy, short-lived showers or thunderstorms.

- *Warm fronts* rather form when a warm air mass moves over a colder air mass. The warm air mass rises gradually, leading to the formation of stratiform clouds. Precipitation associated with warm fronts tends to be more prolonged and gentle compared to cold fronts, often resulting in steady rain that can last for hours or even days.

- *Occluded fronts* occur when a cold front overtakes a warm front, lifting the warm air mass off the ground. This process can lead to complex weather patterns and varying types of precipitation, depending on the characteristics of the air masses involved.

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Frontal rains are characterized by their variability in intensity and duration. Cold fronts typically bring sudden, intense rainfall followed by clearing skies, while warm fronts produce more continuous, lighter rain over an extended period. The nature of the precipitation is influenced by several factors: mountains and other geographical features can enhance rainfall through orographic lifting, where moist air is forced to ascend over elevated terrain; the occurrence and intensity of frontal rains can vary seasonally due to changes in atmospheric circulation patterns, such as the ITCZ in Africa; different regions of Africa experience varying climatic conditions that affect the nature of frontal rains. For example, the Mediterranean climate in North Africa may experience distinct frontal rain patterns compared to the tropical climates in Central and West Africa (Tasah, 2025).

In sub-Saharan Africa, frontal rains play a vital role in the hydrological cycle and have significant implications for agriculture, water resources, and ecosystems. Some key points include:

Agricultural Impact: Many agricultural regions in Africa depend on seasonal rainfall patterns influenced by frontal systems. Understanding these patterns is crucial for farmers to optimize planting and harvesting schedules.

Water Resources: Frontal rains contribute to river flows and groundwater recharge, which are essential for drinking water supplies and irrigation.

Ecosystem Dynamics: The distribution of frontal rains affects biodiversity and ecosystem health. Regions receiving adequate rainfall support diverse flora and fauna, while areas with insufficient precipitation may experience desertification and habitat loss.

Climate Change Implications: As global climate patterns shift, the frequency and intensity of frontal rains may change, impacting water availability and agricultural productivity. Understanding these changes is critical for developing adaptive strategies in vulnerable regions.

The Nature and Causality of Frontal Rainfall in Sub-Saharan Africa (and why they are not *Monsoons*)

Frontal rains in sub-Saharan Africa are typically brought by air masses which have just recently *swept* over the Atlantic Ocean, having been advected over it for a long time. These air masses are usually called Southwest monsoons, as they *invade* that part of the continent from the southwest (Tasah, 2025; Alaka, 1964). They blow in on West Africa from the southwest because they are drawn to the depression created by the fall in air pressure (ITCZ) now located northward around the Tropic of Cancer at $23^1/_2{}^oN$ (Tasah, 2025). These air masses are only called monsoons because they bring rain, and NOT because they create an African monsoonal system. The conventional African monsoonal system is nonexistent (Flohn, 1969; Alaka, 1964).

To better understand African convergent rainfall and why it is not necessarily monsoonal, it is necessary to compare it to the Asian monsoonal system (Flohn, 1969). Monsoons are winds associated with regions where the most rain falls during a particular season; they are usually also the rains in themselves (Johnson, 1969). The monsoonal or convergent circulation over sub-Saharan Africa differs from the Asian system in two important ways. First, their magnitude is much smaller, not only regarding the areas covered, but also in respect to the thickness of the air layers involved (Flohn, 1969). The main reason for this smallness is the limited seasonal variation in the latitudinal position of the main elements of the general circulation, which amounts to not more than 15^o of latitude over sub-Saharan Africa and about 40^o over monsoon Asia. Secondly, no polar air masses are involved in the sub-Saharan African convergent system and the rains here differ much less in main characteristics than in Asia (Pedelaborde, 1958). For this reason, I argue that sub-Saharan African convergent rainfall is not truly monsoonal. It is certain, however, that a genuine seasonal reversal of wind exists over large parts of tropical Africa, in which both air masses on opposite sides of the front or ITZC are well above minimum speed limits and constancy (Pedelaborde, 1958).

The winds that cause convergent rainfall in sub-Saharan Africa are surface winds, which rarely reach levels over 5000 m (Asnani, 1967; Alaka, 1964). The most important feature is the geophysical configuration of the African landmass which causes this regional differentiation between West and East sub-Saharan African

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convergent rainfall systems (Pedelaborde, 1958). In West Africa, there is a great difference between the two winds on opposite sides of the front; but in East Africa, these winds only differ in direction because the nature of the air masses is remarkably similar. In west Africa, the large continental area north of the equator contrasts with the maritime regions of the central Atlantic Ocean, but in East Africa the continent stretches on both sides of the equator, albeit being broader in the northern hemisphere (Asnani, 1967; Alaka, 1964; Pedelaborde, 1958). Other aspects which accentuate the differences between West and East sub-Saharan Africa are the large meridional mountain ranges related to the Great Rift Valley (East African Rift), and the influences of the Asian monsoons experienced only in East Africa (Pedelaborde, 1958). Consider *figure 1.0* below.

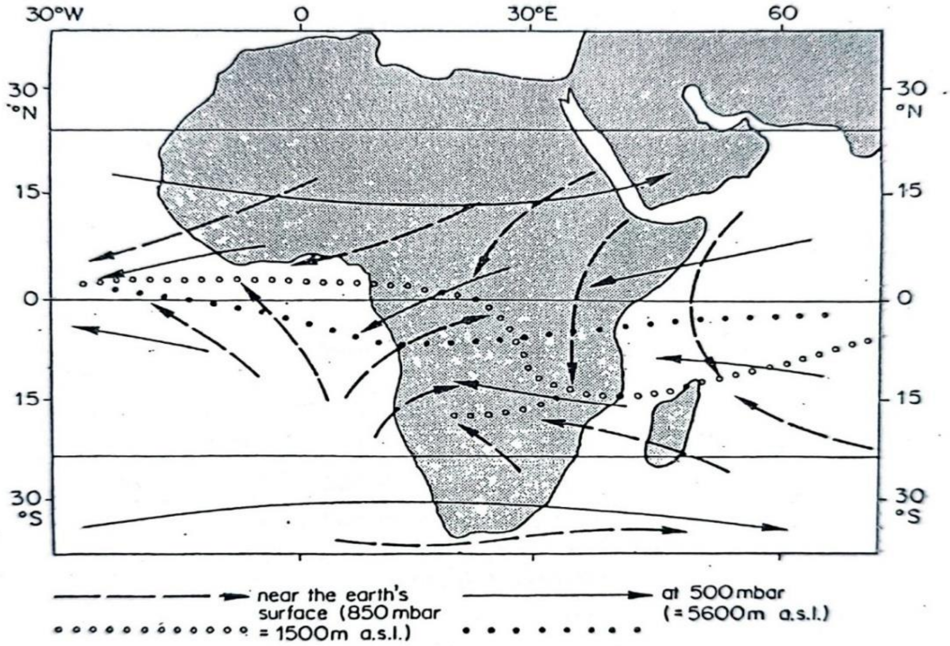

Figure 1.0a: The circulation over Africa during January at the 850 mbar and 500 mbar levels (arrows = winds; dots = convergence zones)

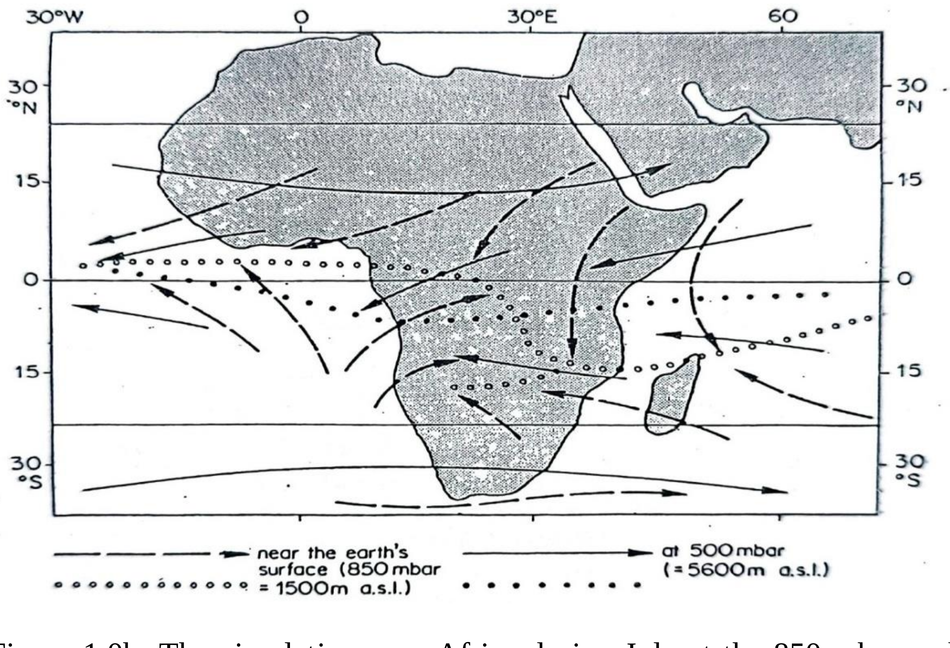

Figure 1.0b: The circulation over Africa during July at the 850 mbar and 500 mbar levels (arrows = winds; dots = convergence zones)

Since a large portion of sub-Saharan Africa's geography consists of extensive highlands, the circulation near the earth's surface is represented by the 850 mbar level, corresponding to about 1500 masl (on *figure 1.0* above). At this elevation, most air streams are relatively free from direct surface effects, such as friction. In

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West Africa, the continent is largely under the influence of northeasterly trade winds during the northern hemisphere's winter, with the ITCZ close to the equator (0^o) and Tropic of Capricorn or 23$^1/_2$^{o}S (Palmen, 1951). These northeasterlies prevail to an altitude of about 3000 m and bring dry and stable air conditions to West Africa. These stable air masses, locally called 'harmattan', carry dust particles from the Sahara Desert over which they originate. Except for the narrow area along the southern coast of West Africa, this is the area's dry season (Palmen, 1951; Pedelaborde, 1958). During the northern hemisphere's summer, high temperatures prevail over the continent, and a thermal low-pressure area builds up around latitude 20^{o}N. Consequently, the ITCZ slowly moves northward to reach a position which at the earth's surface is around 15^{o}N (Palmen, 1951; Pedelaborde, 1958). Generally referred to a *monsoons*, the southwesterly winds now invade the continent as they head for the front or point of convergence, the ITCZ. These southwesterly air masses are warm and humid. Most of the convergent rainfall that ensues usually does not fall near the surface position of the air mass discontinuity, but further south, because the continental air masses are warmer than the oceanic ones, so that they are uplifted (Palmen, 1951; Tasah, 2025). Since only the oceanic air masses produce the precipitation, the zone of maximum convergent rainfall in West Africa is where these air masses are thicker (Pedelaborde, 1958; Tasah, 2025). See *figure 1.1* below.

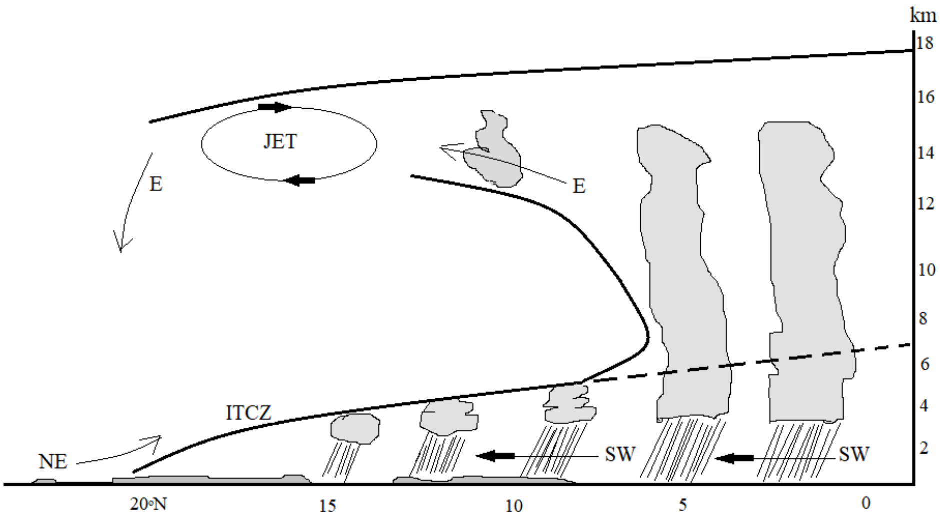

Figure 1.1: Meridional cross-section of the Troposphere in August (Leroux, 1973)

The West African monsoon is relatively shallow, and at the 500 mbar level, the ITCZ remains near the equator throughout the year (Leroux, 1973).

In East Africa, continental influences are effective on both sides of the equator, and consequently, the latitudinal shift of the ITCZ is much larger. In January, it is situated at about 15^{o}S, and so most of East Africa is under the influence of northeasterly winds, which then become northwesterlies once south of the equator, as shown on *figure 1.0* (Leroux, 1973). Since these winds are largely of continental origin, the produce little convergent rainfall over East Africa. The only areas with convergent rains during this season are those situated near the main zones of convergence (Leroux, 1973; Tasah, 2025). In July, the ITCZ is at about 15^{o}S, and over East Africa, southwesterly winds prevail. Again, these winds bring little (convergent) rains. These air masses blowing over East Africa now are of partly of continental origin, coming from the high-pressure area over southern Africa. But even those air masses which come from the Indian Ocean are dry, having shed most of their moisture on the steep eastern mountain slopes of Madagascar (Tasah, 2025; Flohn 1969). As such, in most of East Africa convergent rainfall is very little, being concentrated during the intermediate seasons, when the ITCZ moves over the region on its way to the opposite hemisphere (Tasah, 2025; Flohn, 1969; Leroux, 1973).

Convectional Rainfall

Convectional rainfall is a crucial aspect of the hydrological cycle, particularly in tropical and subtropical regions. This type of rainfall is characterized by its formation process, which involves the vertical movement of warm, moist air. Understanding convectional rainfall an examination of its mechanism, characteristics, geographical distribution, and implications for both natural ecosystems and human activities (Apchu et al, 2015).

The formation of convectional rainfall is primarily a result of solar heating and the subsequent rise of warm air. Conventional Rainfall is formed when air on the surface of the earth and few metres above it is heated by the sun (Zikhali et al, 2010). As the air is heated, it becomes lighter (water vapor). The lighter air rises, cools down, and then condenses on the condensation nuclei in the atmosphere. When water vapor rises further, it converges and moves gradual upwards. This is due to the fact that there are few areas to be covered by the converging air. As the air converges, it condenses to form thick cumulous clouds. The rising clouds become heavier and unstable.

We now consider a closer examination of this formation process: during the ascent, the air mass remains warmer than the surrounding environmental air and is likely to become unstable, with towering cumulonimbus clouds forming (Waugh, 2005). These unstable conditions, possibly augmented by frontal and/orographic uplift, force the air to rise in a *chimney*. The updraught is maintained by energy released as latent heat at both the condensation and freezing levels. The cloud summit is characterized by ice crystals in an anvil shape, the top of the cloud being flattened by upper air movements (Waugh, 2005). When the ice crystals and frozen water droplets (hail) become large enough, they then fall in a downdraught. The air through which they fall remains cool as heat is absorbed by evaporation. The downdraught reduces the warm air supply to the *chimney*, and therefore limits the lifespan of the storm, which are usually accompanied by thunder and lightning (Houghton, 1954; List, 1958).

As the raindrops are carried upward into colder regions, they freeze on the outside. This ice-shell compresses the water inside until the shell bursts and the water freezes into positively-charged ice crystals, while the heavier shell fragments, which are negatively-charged, fall toward the cloud base and induce a positive charge on the earth's surface (Waugh, 2005). This type of rainfall is common in West Africa and is followed by lightning and thunderstorms as its associated character (Mastrorillo, et al (2016). *Figure 1.*2 below demonstrate the formation process of convectional rains.

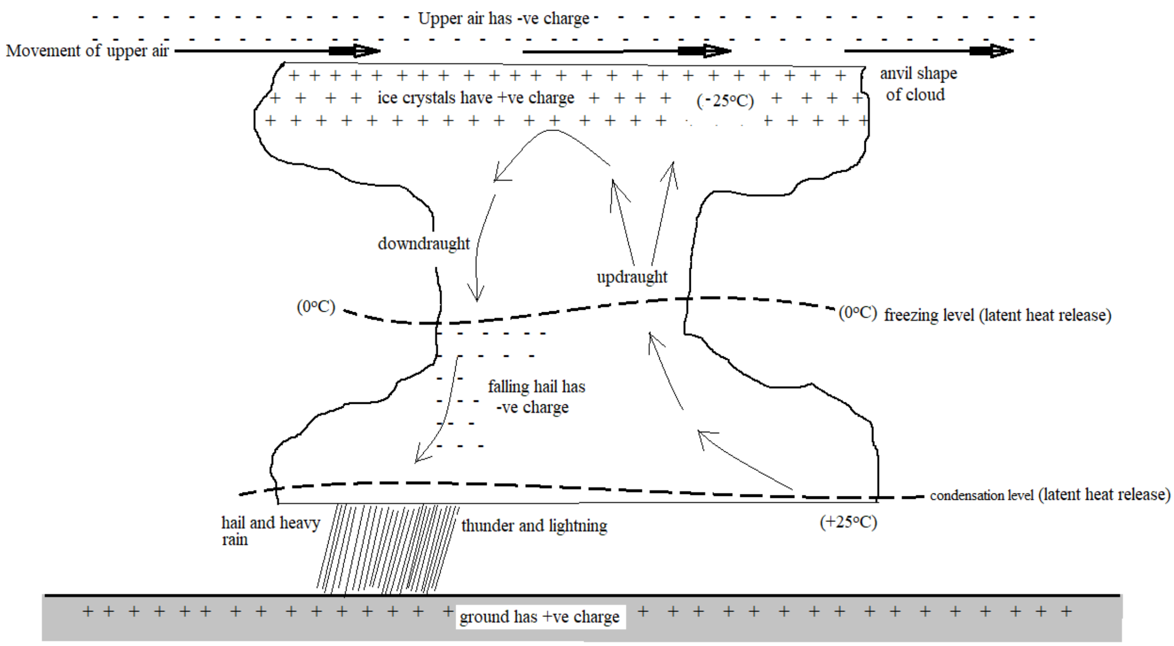

Figure 1.2: Formation of Convection Rainfall (Waugh, 2005)

The Nature of Convectional Rainfall in Sub-Saharan Africa (*Clausius–Clapeyron Relation analysis*)

The intensity of extreme precipitation is expected to increase with (increase) temperature at a rate consistent with the available moisture, which is determined by the Clausius–Clapeyron (C-C) relation. The C-C rate is approximately 6%–7% 8C21 and is found to largely hold for observations and model simulations (Allen and

Ingram 2002; Trenberth et al. 2003; Westra et al. 2013; Zhang et al. 2017). The scaling between extreme precipitation and temperature in Sub-Saharan Africa varies with many factors including the magnitude of extremes and the time scale. Precipitation extremes of a shorter time scale tend to be more sensitive to a temperature change. In particular, subdaily or hourly precipitation extremes exhibit enhanced scaling up to a doubled C-C rate. Such an increase in precipitation intensity that exceeds thermodynamic constraints is known as a super C-C scaling (Lenderink and van Meigjaard 2008; Berg et al. 2013). The super C-C scaling has been observed in many parts of Sub-Saharan Africa. There are different mechanisms concerning the super C-C scaling. One is the statistical argument that the super C-C scaling results from a systematic change from large-scale to convectional rainfall events in sub-Saharan Africa (Haerter and Berg 2009; Berg and Haerter 2013). In this case, the convective and large-scale events separately both follow the C-C rate, while the resulting dependency is a super C-C scaling because of the transition between dominant precipitation types from the large-scale to convectional events. The other argument is that the super C-C scaling is a property of convective events (Berg et al. 2013; Moseley et al. 2013), which involves physical feedback processes associated with increases in the convective available potential energy (CAPE) and the latent heat release with temperature (Trenberth et al. 2003; Panthou et al. 2014). Thereby, convective extreme events inherently follow a super C-C scaling and the increased contribution of convectional rainfall types shifts the total scaling from the C-C to the super C-C rate at around 128C (Berg et al. 2013). In addition to the super C-C scaling, many studies reported the upper limit of the scaling such that the scaling levels off or declines at high temperatures above 248C. This behaviour is suggested to be due to the moisture limitation to the convective system at high temperatures, which can be seen from the decrease in relative humidity or the stabilized scaling obtained when using dewpoint temperature (Hardwick Jones et al. 2010; Lenderink et al. 2011; Panthou et al. 2014; Westra et al. 2014).

Given the different scaling results across sub-Saharan regions, West Africa most especially, separating precipitation types into the large-scale and convective events, and analyzing their contribution to the total scaling is critical to better understanding mechanisms relevant for the region. Generally, stratiform events have longer durations and lower intensities than convective events and predominantly occur at lower temperatures (Berg et al. 2013). However, the influence of different precipitation types in West Africa on the scaling has only been examined in a very limited way. In particular, the role of convective precipitation in the scaling remains to be determined over many regions of sub-Saharan Africa (Utsumi et al. 2011; Miao et al. 2016). This question has an important implication for climate change projection given that Western Africa is expected to experience more frequent and intensified extreme events under global warming (e.g., Min et al. 2015; Ahn et al. 2016; D. Lee et al. 2017). Hence, this study aims to examine the subdaily precipitation–temperature relationship in sub-Saharan Africa and to investigate the contribution of convectional precipitation to the scaling pattern.

Convectional rainfall is a vital component of Africa’s climate system, influencing both natural ecosystems and human activities across sub-Saharan Africa. Their formation process explained above is closely tied to local temperature variations and humidity levels, resulting in highly localized precipitation events that can have profound implications for agriculture, water resources, and biodiversity. Understanding convectional rains is essential for effective resource management and climate adaptation strategies in Africa’s diverse landscapes. As climate change continues to impact weather patterns globally, monitoring and studying convectional rains will be crucial for anticipating future challenges related to water availability and food security in sub-Saharan Africa.

Research Problem and Objectives of the Study: Cameroon

Nature of Rainfall Unpredictability and Unreliability in Cameroon

Rainfall is a critical component of the climate system, particularly in regions like Cameroon, where agriculture, water supply, and overall livelihoods are intrinsically linked to seasonal precipitation patterns. However, recent trends indicate a growing unreliability and unpredictability of rainfall in Cameroon, largely attributed to the impacts of climate change. (IPCC, 2021). This essay explores the factors contributing to these changes, the consequences for the environment and society, and the broader implications for sustainable development in the region.

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Historically, Cameroon has experienced a relatively predictable rainy season, characterized by distinct wet and dry periods (Tasah, 2025). However, climate change has introduced significant variability into these patterns (Sultan, B., et al., 2019). Research indicates that average temperatures in Cameroon have increased over the past few decades, leading to alterations in atmospheric conditions that influence rainfall. The Intergovernmental Panel on Climate Change (IPCC) reports that many regions in Africa, including Cameroon, are experiencing shifts in precipitation patterns, with some areas facing increased rainfall, while others suffer from prolonged dry spells (IPCC, 2021). One notable phenomenon is the increasing frequency and intensity of extreme weather events. These include heavy downpours that lead to flooding as well as extended drought periods that can devastate crops and disrupt water supply. For instance, a study by Oxfam (2019) highlights how the 2016-2017 agricultural season was marked by erratic rainfall, resulting in significant crop failures across the country. Such extremes make it difficult for farmers to predict planting and harvesting times, resulting in reduced agricultural productivity and food insecurity (UNDP, 2018).

Sub-Saharan Africa, especially Cameroon, is experiencing significant changes in rainfall patterns, which pose profound challenges to agricultural productivity and food security. As climate change continues to exacerbate these shifts, the urgency for climate adaptation in agriculture and policy becomes increasingly critical. Recent studies have highlighted that rainfall variability has intensified, with some regions facing prolonged droughts while others experience extreme flooding (Niang et al., 2014). This unpredictability undermines the traditional farming practices that millions of smallholder farmers rely on, leading to reduced crop yields and increased vulnerability to food shortages (Mastrorillo et al., 2016). Consequently, there is an urgent need for adaptive strategies that incorporate climate-resilient agricultural practices and policies that support farmers in navigating these changes.

Rainfall analysis serves as a vital tool in informing these adaptation initiatives. By utilizing historical and predictive rainfall data, policymakers can identify regions at greatest risk of drought or flooding and develop targeted interventions (Gbetibouo et al., 2010). For instance, improved forecasting models can help farmers make informed decisions about planting and harvesting times, thus optimizing their yield potential despite climatic uncertainties. Furthermore, integrating rainfall data into national agricultural policies can enhance resource allocation, ensuring that infrastructure investments are directed toward areas most susceptible to climate impacts (World Bank, 2016). As such, a robust understanding of current trends in rainfall is essential for creating adaptive frameworks that not only bolster agricultural resilience but also promote sustainable development in Sub-Saharan Africa amidst the looming threats of climate change.

Climate Change Impact on Rainfall Reliability

The unpredictability of rainfall in Cameroon can be traced back to several interrelated factors influenced by climate change. First, the alteration of global weather patterns due to rising greenhouse gas emissions affects regional climates (Tasah, 2025). Changes in sea surface temperatures, particularly in the Atlantic Ocean, can shift wind patterns and moisture availability, leading to irregular rainfall distribution across the country (Hulme et al., 2001). Moreover, deforestation and land-use changes exacerbate the situation. In Cameroon, rapid urbanization and agricultural expansion have led to significant deforestation, which disrupts local hydrological cycles. According to a report by the Food and Agriculture Organization (FAO) (2020), Cameroon lost approximately 1.5 million hectares of forest between 2000 and 2018. Trees play a vital role in maintaining moisture levels in the atmosphere; their removal not only reduces rainfall but also contributes to soil degradation and erosion. Consequently, the loss of forest cover further destabilizes the climate system, perpetuating a cycle of unpredictability (Pretty, J., et al., 2018).

Socio-economic Implications

The unreliability of rainfall has profound implications for Cameroon's economy and society. Agriculture remains the backbone of the country's economy, employing a significant portion of the population (Sultan, B., et al., 2019). Farmers rely on seasonal rains for crop cultivation; thus, unpredictable rainfall can lead to crop failures, reduced yields, and ultimately food insecurity. The World Bank (2020) notes that approximately 60% of Cameroon's population is engaged in agriculture, making them particularly vulnerable to climatic changes.

In addition to agricultural impacts, unreliable rainfall poses challenges for water management. Many communities in Cameroon rely on rain-fed systems for their water supply. As rainfall becomes increasingly erratic, water scarcity becomes a pressing issue, leading to conflicts over resources and exacerbating poverty levels (Mastrorillo et al., 2016). Vulnerable populations, particularly those in rural areas, bear the brunt of these changes, facing heightened risks of malnutrition and health issues related to waterborne diseases (Sultan, B., et al., 2019).

Objectives of the Study

This research fundamentally seeks to understand how frontal and convectional rainfall patterns differ across various latitudinal zones in Sub-Saharan Africa, specifically, and with evidence of a study along the meridional cross-section of Cameroon from Kribi to Maroua, and what meteorological factors contribute to these variations. It aims to analyze and compare the characteristics of frontal and convectional rainfall across Cameroon's meridional transect, focusing on spatial variability, trend patterns, and implications for water and agriculture in and around Cameroon.

One of the prime objectives of this study is to systematically analyze the spatial distribution and intensity of both frontal and convectional rainfall across different latitudes in Cameroon. By focusing on the transition from Kribi in the southern region to Maroua in the north, this study aims to map out how rainfall types vary in frequency and volume along this meridional cross-section. I also investigate the key meteorological factors that play a role in the formation and distribution of frontal and convectional rains within the study area. Factors such as temperature gradients, humidity levels, prevailing wind patterns, and atmospheric pressure systems will be assessed to understand their influence on rainfall variability.

This research focuses on comparing the characteristics of frontal rainfall with those of convectional rainfall. It examines aspects such as the frequency of occurrence, duration of rainfall events, and intensity levels across different latitudinal zones, providing insights into how these two types of rainfall manifest in the region. I also seek to assess how seasonal changes impact the distribution and occurrence of frontal and convectional rains in Cameroon, and identify peak periods for each type of rainfall while analyzing seasonal trends and their implications for local climate patterns.

Furthermore, it seeks to evaluate the ecological implications of varying rainfall patterns on local agriculture, water resources, and biodiversity within the latitudinal zones of Cameroon, making this study explore how changes in rainfall affect crop yields, water availability, and ecosystem health.

Lastly, it aims to provide actionable recommendations for local farmers and policymakers based on the findings of the study. This study focuses on strategies for adapting to changing rainfall patterns due to climate variability, emphasizing sustainable agricultural practices that can enhance resilience in the face of these changes.

SCIENTIFIC PROCEDURE (METHODOLOGY):

A General Look

For this study, a combination of satellite data and ground-based meteorological station records were utilized to ensure comprehensive and accurate analysis. The selection of satellite data from TRMM and GPM, ground-based observations from Meteo-Cameroon, climatological datasets from global repositories, and regional climate models provided a comprehensive framework for understanding the distribution of frontal and convectional rains across Sub-Saharan latitudes in Cameroon. Each data source contributed unique strengths that enhance the robustness of the research methodology, ensuring that findings were accurate, reliable, and contextually relevant. This multi-faceted approach will not only enrich our understanding of current rainfall patterns but will also equip us with valuable insights into future climatic changes that may impact this vital region.

Satellite Data

Satellite data provides a broad and detailed perspective on rainfall patterns, particularly useful for regions with limited ground-based observations. The use of remote sensing technology allows for the observation of large areas over time, facilitating the analysis of spatial and temporal variations in precipitation.

The **Tropical Rainfall Measuring Mission (TRMM)** satellite, launched by NASA and JAXA, is one of the primary sources for estimating rainfall in tropical regions. TRMM provides high-resolution rainfall estimates through its Precipitation Radar (PR) and Microwave Imager (TMI), making it invaluable for understanding convectional rain patterns (Huffman et al., 2007). Additionally, the **Global Precipitation Measurement (GPM)** mission continues to build upon TRMM's legacy by providing advanced precipitation measurements that improve our understanding of rainfall distribution across latitudes (Skofronick-Jackson et al., 2017).

Justification for Satellite Data

Comprehensive Spatial Coverage: Satellite data, particularly from the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM) mission, offers extensive spatial coverage that is essential for analyzing rainfall patterns over large areas such as Sub-Saharan Africa. Given the diverse topography and climate zones in Cameroon, satellite observations allow researchers to capture rainfall data in regions where ground-based measurements may be sparse or non-existent.

High Temporal Resolution: Both TRMM and GPM provide high temporal resolution data, enabling the analysis of rainfall events on daily to monthly scales. This is crucial for understanding the dynamics of both frontal and convectional rainfall, which can vary significantly over short periods. The ability to monitor these variations helps in identifying patterns related to seasonal changes and climate anomalies.

Advanced Precipitation Estimation Techniques: The methodologies employed by TRMM and GPM utilize advanced remote sensing technologies, including radar and microwave sensing, to estimate precipitation with high accuracy. These techniques are particularly effective in capturing the intensity and distribution of rainfall associated with convective systems, which are prevalent in tropical regions like Cameroon. The use of these sophisticated tools enhances the reliability of the data, allowing for more precise analyses of rainfall characteristics.

Validation and Calibration: Satellite data can be validated against ground-based measurements, providing an opportunity to calibrate estimates and improve accuracy. This dual approach allows researchers to cross-verify findings and ensures that conclusions drawn from satellite observations are robust. The integration of satellite data with ground truth enhances the reliability of rainfall estimates, particularly in heterogeneous environments.

Meteorological Stations

Ground-based meteorological stations are critical for validating satellite data and providing localized precipitation measurements. The **Cameroon Meteorological Agency (Meteo-Cameroon)** operates a network of weather stations across the country that collect daily rainfall data, temperature, humidity, and other relevant meteorological variables. These stations are crucial for understanding the microclimates within Cameroon and offer insights into both frontal and convectional rainfall events. Research has shown that integrating ground-based measurements with satellite-derived data enhances the accuracy of precipitation estimates (Adler et al., 2003). Therefore, data from these meteorological stations will be used to corroborate satellite observations and refine our understanding of rainfall distribution patterns.

Justification for Meteorological Stations (Meteo-Cameroon)

Localized Data Collection: Ground-based meteorological stations operated by Meteo-Cameroon provide localized data that is essential for understanding microclimatic variations within the country. Rainfall patterns can differ significantly over short distances due to topographical features, land use, and local weather

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phenomena. Ground stations allow for the collection of detailed, site-specific data that can elucidate these variations.

Long-Term Historical Records: Meteorological stations often have long-term historical records of precipitation and other climatic variables. This historical context is vital for identifying trends and changes in rainfall patterns over time, especially in the face of climate change. Analyzing historical data can reveal shifts in seasonal rainfall patterns, frequency of extreme weather events, and overall changes in climate that impact both frontal and convectional rains.

Validation of Satellite Data: The use of ground-based measurements is crucial for validating satellite-derived precipitation estimates. By comparing satellite data with measurements from meteorological stations, researchers can assess the accuracy of satellite observations and make necessary adjustments to improve their reliability. This validation process is particularly important in regions where satellite data may be less accurate due to factors like cloud cover or terrain.

Climatological Data Repositories

In addition to satellite and station data, climatological databases such as the **World Bank Climate Data** and the **National Oceanic and Atmospheric Administration (NOAA)** provide historical climate datasets that are essential for examining long-term trends in rainfall patterns. These datasets offer insights into how climatic factors influence the distribution of frontal and convectional rains in Sub-Saharan Africa (Fischer et al., 2012).

Justification for Climatological Data Repositories

Access to Comprehensive Climate Datasets: Climatological databases such as those provided by the World Bank Climate Data and NOAA offer access to a wealth of historical climate datasets. These repositories include various climate variables beyond just precipitation, such as temperature, humidity, and wind patterns, which are essential for understanding the broader climatic context influencing rainfall distribution.

Facilitating Comparative Studies: These databases allow for comparative studies across different regions and time periods. Researchers can utilize this information to contextualize findings within a larger framework of climate variability and change, enhancing the depth of analysis regarding how frontal and convectional rains are impacted by broader climatic trends.

Support for Climate Change Projections: Climatological data repositories often include projections related to climate change scenarios. Understanding how potential future changes in temperature and atmospheric conditions may affect rainfall patterns is critical for developing adaptive strategies in vulnerable regions like Cameroon. This foresight is essential for planning in sectors such as agriculture, water resource management, and disaster preparedness.

Regional Climate Models

To further enhance our analysis, regional climate models (RCMs) such as those developed under the **Coupled Model Intercomparison Project (CMIP)** can provide projections of future rainfall patterns under various climate scenarios. These models help in understanding how changes in climate variables may affect precipitation distributions in Cameroon (Giorgi Mearns, 2002).

Justification for Regional Climate Models

Future Projections of Rainfall Patterns: Regional climate models (RCMs) developed under initiatives like the Coupled Model Intercomparison Project (CMIP) provide crucial insights into future climate scenarios. These models simulate how changes in greenhouse gas emissions and land use may influence regional climates, including precipitation patterns. Utilizing RCMs allows researchers to forecast potential shifts in rainfall distribution due to climate change.

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Understanding Climate Dynamics: RCMs enhance our understanding of the complex interactions between various climatic factors that influence rainfall. By incorporating local topography, land surface characteristics, and atmospheric dynamics, these models provide a more nuanced view of how frontal and convectional rains may evolve under changing climatic conditions.

Informing Policy and Decision-Making: The insights gained from RCMs can inform policymakers and stakeholders about potential future scenarios, enabling better planning and risk management strategies related to water resources, agriculture, and disaster response. This proactive approach is essential for building resilience in communities that depend on predictable rainfall patterns for their livelihoods.

Study Area: Length Of Cameroon (Kribi To Maroua)

Cameroon, located in Central Africa, is often referred to as "Africa in miniature" due to its diverse geography and climate (Mastrorillo, M., et al. 2016). Bordered by Nigeria to the west, Chad to the northeast, and the Central African Republic to the east, it has a coastline along the Atlantic Ocean to the southwest. The country spans approximately 475,442 square kilometers and has a population of around 27 million people, resulting in a population density of about 57 people per square kilometer World Bank (2020). Cameroon is characterized by a variety of altitudes, ranging from the coastal plains at sea level to the highlands of the Adamawa Plateau, which reach elevations of over 1,500 meters. The country's geography includes the volcanic peaks of the Western Highlands, such as Mount Cameroon, which stands at 4,095 meters, making it the highest point in West Africa. This diverse topography contributes to a range of climatic zones, from the humid tropical climate along the coast, with average annual rainfall exceeding 3,000 millimeters, to the drier savannah climate in the northern regions (Mastrorillo, M., et al. 2016). The central and western highlands experience a temperate-like type of climate with cooler temperatures and seasonal rainfall, while the northern areas are characterized by a more arid climate with distinct wet and dry seasons. This rich combination of geographical features and climatic conditions supports a wide variety of ecosystems and agricultural practices across the country (Sultan, B., et al. 2019).

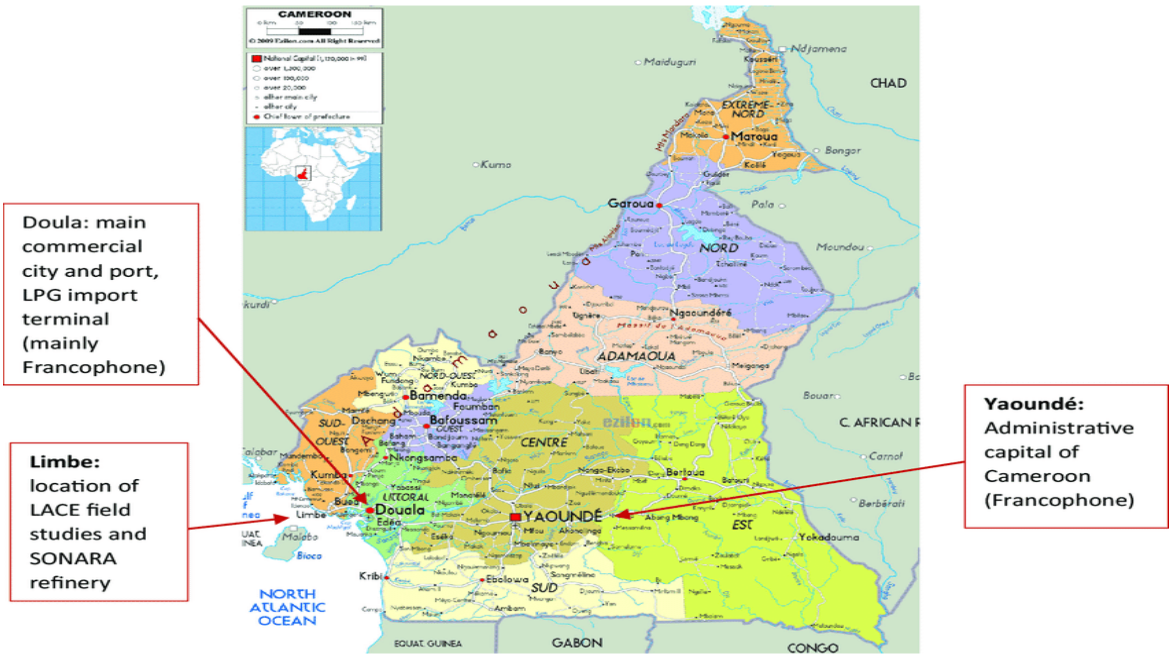

Figure 2.0: Map to show geographical position of Cameroon in Africa

Cameroon, as "Africa in miniature," serves as a microcosm of the continent's diverse climatic and ecological zones. Spanning approximately 1,000 kilometers from Kribi in the South Region to Maroua in the Far North Region, Cameroon showcases a remarkable gradient of environmental conditions, influenced by its unique geographical features and latitudinal position (Mastrorillo, M., et al. 2016). This geographical diversity makes it an ideal case study for understanding the latitudinal distribution of frontal and convectional rains, particularly as they relate to the broader climatic patterns observed across West Africa. Cameroon's positioning along the Gulf of Guinea and its proximity to both the Atlantic Ocean and the Sahelian region creates a complex interplay of climatic influences. The country's geography is characterized by a variety of landscapes, including coastal plains, mountainous regions, and expansive savannas. The southern part of the country, particularly around Sangmelima, is characterized by dense tropical rainforests that thrive in a humid climate. This region experiences high levels of rainfall, primarily through convectional processes that are driven by intense solar heating. The Intertropical Convergence Zone (ITCZ), which oscillates north and south with the seasons, plays a critical role in this dynamic, bringing about significant rainfall during the wet season (Mastrorillo, M., et al. 2016).

As one moves northward towards Kousseri, which lies near the border with Chad and close to Lake Chad, the climate shifts dramatically. The transition from lush tropical forests to drier savanna and eventually to semi-arid conditions reflects a significant change in rainfall patterns. In this northern region, the influence of the ITCZ diminishes, and frontal systems associated with the West African Monsoon become increasingly relevant. These systems are characterized by the convergence of moist air from the Atlantic Ocean with dry air from the Sahara Desert, leading to distinct rainfall patterns that differ markedly from those found in the south (Oxfam, 2019).

Cameroon Climate Variability: Frontal Vs. Convectional Rains

The distinction between frontal and convectional rains is crucial for understanding Cameroon's climate. In the southern parts, such as in Kribi and Sangmelima, convectional rains dominate due to localized heating (Mastrorillo, M., et al. 2016; Oxfam, 2019). The intense solar radiation during the day causes rapid evaporation of moisture from the surface, leading to the formation of cumulus clouds. As these clouds continue to rise and cool, they eventually release their moisture in the form of heavy rain showers. This process is often sporadic but can lead to significant rainfall events that support the rich biodiversity and agriculture of the region (Mastrorillo, M., et al. 2016).

In contrast, in northern Cameroon, around Maroua and Kousseri, rainfall is more influenced by frontal systems. These systems are typically associated with larger-scale atmospheric circulation patterns and are characterized by long-lasting rain events that can be more evenly distributed over time. The arrival of these fronts can lead to substantial precipitation during specific seasons, which is vital for agricultural practices in this region where farmers depend on seasonal rains for crop production. The variability in rainfall patterns between these two regions underscores the importance of understanding both types of precipitation when assessing agricultural viability and water resource management (Sultan, B., et al. 2019).

Cameroon Climate Reflection Of Sub-Saharan Africa: West Africa

The climatic characteristics of Cameroon reflect broader trends observed in sub-Saharan Africa, especially West Africa. The country's diverse ecosystems — from coastal mangroves to arid northern landscapes — mirror the climatic variations found throughout the sub-region. For instance, countries such as Nigeria and Ghana experience similar climatic influences due to their geographical proximity and latitudinal alignment with Cameroon (Sultan, B., et al. 2019). The seasonal migration of the ITCZ affects not only Cameroon but also neighbouring countries, resulting in synchronized wet and dry seasons across much of West Africa (Sultan, B., et al. 2019; Oxfam 2019).

Studying rainfall patterns in Cameroon provides insights into the larger climatic dynamics at play in West Africa. For example, changes in the ITCZ's position due to climate change could have profound implications for agricultural productivity not just in Cameroon but throughout the region. Additionally, understanding how frontal rainfall patterns are shifting can help predict potential droughts or flooding events that may impact food security and livelihoods across West Africa (Mastrorillo, M., et al. 2016; UNDP, 2018).

Socioeconomic Implications

The implications of these climatic variations extend beyond environmental considerations; they significantly affect socioeconomic factors such as agriculture, water supply, and local economies. In southern Cameroon,

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where convectional rains support crops like cocoa and oil palm, farmers are highly dependent on consistent rainfall patterns for their livelihoods (World Bank, 2020). Conversely, in northern regions like Kousseri, where agriculture is more reliant on frontal rains for crops such as millet and sorghum, farmers must adapt their practices based on seasonal predictions.

Furthermore, climate change poses additional challenges to these established patterns. Increased temperatures can lead to altered precipitation patterns, affecting both the timing and intensity of rainfall (Hulme, M., et al., 2001). This unpredictability can hinder agricultural planning and exacerbate food insecurity in a region already vulnerable to climate variability. Local governments and organizations must therefore prioritize sustainable agricultural practices and water resource management strategies that account for these changing climatic conditions (IPCC, 2021).

Cameroon's geographic and climatic diversity makes it an exemplary study area for examining the latitudinal distribution of frontal and convectional rains in sub-Saharan Africa. Its classification as "Africa in miniature" underscores how its climatic patterns can illuminate broader trends in West Africa. Understanding these dynamics is essential for effective resource management and agricultural planning, particularly as climate change continues to impact weather patterns across the region. Through this exploration, we gain valuable insights into the intricate relationship between geography, climate, and rainfall distribution in one of Africa's most diverse nations. By delving deeper into Cameroon's climatic variations and their implications for both local communities and broader regional trends, we can better appreciate the complexities of environmental management in a changing world. This knowledge not only enhances our understanding of Cameroon's unique ecological landscape but also serves as a vital resource for policymakers aiming to foster resilience against climate change impacts in West Africa.

Figure 2.1: Climatic map of Cameroon

Scientific Analysis

The general hypothesis of this work is that there is a general reduction in intensity of both frontal and convectional rains from Kribi in the south (Guinean type of Equatorial Climate) toward Maroua in the north (Sahel Tropical Climate) (Mastrorillo, M., et al., 2016). To support this hypothesis, data from eight selected weather stations across Cameroon was compared using the following statistical methods for comparative

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analysis between the stations: normality test, coefficient of variation, Mann Kendall Trend Test, and Precipitation Concentration Index. For readability, I used fewer stations (the main regional stations) compared to the many more existing stations in the different regions.

The World Meteorological Organization (WMO, 2018) recommends an observation period of more than 30 years to ensure the independence of climate data time series to cope with natural climate variability. This fact is because shorter time series are more sensitive to the values at the start and end of the series. Therefore time-series data of rainfall from 1983 to 2021 for meteorological stations across Cameroon were created. These data were derived from a fusion of satellite rainfall estimates from African Rainfall Climatology version 2 (ARC-2) adjusted with weathers stations data using the period of overlap of the two data sources, then extended over the study period (UNDP, 2018). *Table 2.0* presents the general geographic information of the selected weather stations (three extra stations are, for now, added, but will not be selected for final analysis). These stations called reference weather stations in this study are those among many other stations in Cameroon with no more than four years of missing data. This is the criterion that motivated their choice for the research.

Table 2.0: General geographic information of selected weather stations

CODE	STATION NAME	LATITUDE	LONGITUDE	ALTITUDE
FKYS	**Yaounde, Nsimalen**	**3.848ºN**	**11.502ºE**	**704 masl**
FKDU	**Douala Int. Airport**	**4.005ºN**	**9.708ºE**	**10 masl**
FKGR	**Garoua Int. Airport**	**9.303ºN**	**13.385ºE**	**120 masl**
FKBC	**Bamenda Airport**	**5.963ºN**	**10.159ºE**	**1600 masl**
FKMR	**Maroua Salak Airport**	**10.593ºN**	**14.319ºE**	**350 masl**
FKBU	**Bertoua Airport**	**4.583ºN**	**14.097ºE**	**580 masl**
////	**Kribi Weather Station**	**4.548ºN**	**9.905ºE**	**5 masl**
////	**Limbe Weather Station.**	**4.020ºN**	**9.706ºE**	**20 masl**

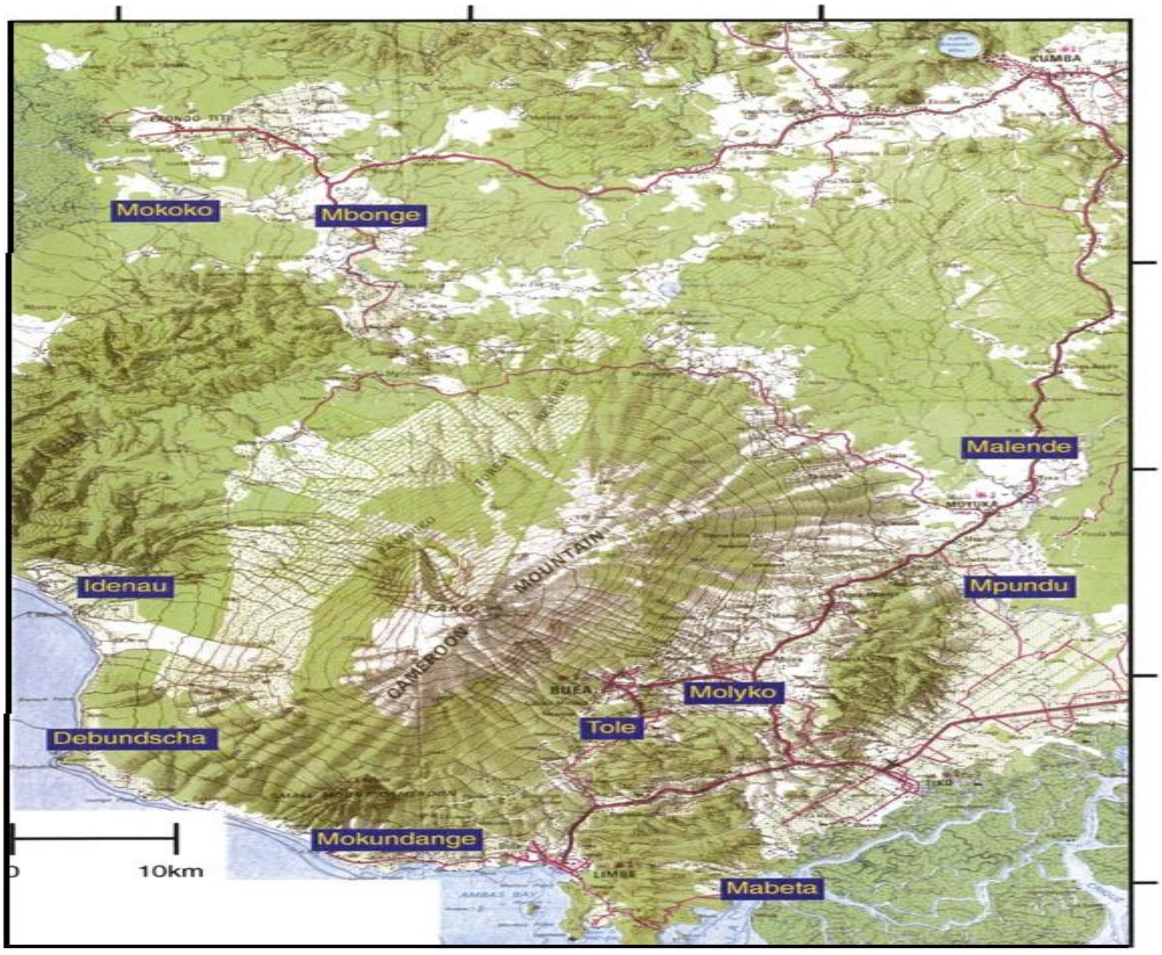

Figure 2.2: Map to show weather stations around Mount Cameroon

Procedures

Normality Test:

Assessment of the normality of data is a prerequisite for selecting the best statistical methods for data analysis. In this regard, the available two main methods for assessing normality are graphical and numerical including statistical tests (Machin et al. 2007; Bland et al. 2015). This study applied a normality test using the Kolmogorov-Smirnov test (KS-test) method. KS-test is recommended when sample size is greater than 50 (Mishra et al. 2019). As such, daily, monthly and annual rainfall for all the stations were subjected to normality tests. The null hypothesis states that data are taken from a normal distributed population and when $P > 0.05$, null hypothesis is accepted and data are called as normally distributed.

Coefficient of Variation (*CoV*):

The research uses *CoV* to examine the variability in rainfall. The higher value of *CoV* is an indicator of larger rainfall variability, and vice versa. The equation of *CoV* is as follows: $CoV = \Theta\ \mu \times 100$ (1) Where *CoV* is the coefficient of variation; Θ is the standard deviation and $\boldsymbol{\mu}$ is the mean of rainfall over the studied period. *CoV* was computed to classify the degree of rainfall variability according to El-Mahdy, 2021 and Hael, 2021. *CoV* less than 20 indicate low variability, *CoV* greater than 20 and less than 30 indicate moderate variability; and *CoV* greater than 30 indicate high variability (Royé and Martin-Vide, 2017).

Mann-Kendall Trend Test:

From the wide types of trend analysis methods, the non-parametric Mann-Kendall trend test (Mk-test) proposed by Mann (1945) and Kendall (1975) was used. This test does not require the data to be normally distributed and has low sensitivity in abrupt breaks due to inhomogeneous time-series (Tabari et al. 2011) and have been widely employed to detect monotonic trends in the time series of hydrometeorological variables (Asfaw et al. 2018; Xu et al. 2018; Zakwan and Ara, 2018; Mohamed and El-Mahdy, 2021; Mohamed et al. 2022). The MK test is grounded on a null hypothesis (H0), which indicates that there is no trendthe data are independent and randomly ordered-and this is verified against the alternative hypothesis (Ha), which supposes that there is a trend (Koudahe et al. 2018). In the calculation, the value of Z is the judgement criterion for the trend change (Xu et al. 2018). When $|Z| \leq 1.96$, the null hypothesis **H0** is accepted, indicating that there is no significant trend at the 0.05 significance level. $|Z| \geq 1.96$ demonstrates the trend of the time series is statistically significant. It must be noted that a positive Z indicates that the sequence has an increasing trend, while a negative Z reflects a declining trend.

Precipitation concentration index:

Precipitation Concentration Index (PCI) was used to assess the monthly heterogeneity of rainfall amounts. PCI is a useful indicator to determine the precipitation changes of a specific region and defined as the ratio between sum of squared monthly rainfall to the square of annual rainfall (Bhattacharyya and Sreekesh, 2022). The PCI, proposed by Oliver (1980) and further modified by De Luis et al. (2011), is used for the calculation of the annual PCI following:

$$\mathbf{PCI = 100 \times \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2}}$$

PCI values of less than 10 indicate quite uniform annual distribution of rainfall, values between 11 to 15 denote a moderate rainfall distribution, 16 to 20 denote irregular rainfall distribution and above 20 represent a strong irregularity of rainfall distribution Asfaw et al. 2018 and Rahman et al. 2019, Pawar et al. 2022.

Comparative analysis between stations

Comparison of several groups or independent samples requires the application of an appropriate statistical test. In this regard, the common statistical tests are ANOVA for normally distributed samples or groups and the

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Kruskal Wallis test (KW-test) for non-normally distributed samples or groups (Cabral Júnior and Lucena, 2019). In this study, the KW-test test was used since the hypothesis of the normality distribution of data was rejected at 1% of statistical significance, as verified by the KS-test (p-value: 0.5). As the KW-test compares (paired or unpaired) k samples based on the null hypothesis that the median differences within groups are not significant. In this research the groups were formed by daily/annual rainfall data for individual met stations to check the rainfall pattern similarity and difference (synchronicity and asynchronicity) during the conventional 35-years climate duration. The null hypothesis is that there are no significant differences between the rainfall medians in the pattern in the study area.

Measurement Techniques

Rainfall amounts were measured using specific gauges installed at the weather stations to collect rainfall. The rainfall was measured directly in millimetres. Information from these stations was transferred via Wi-Fi, satellite, GPS or telephone to central monitoring networks, from where it was immediately updated and integrated into weather models.

Data on rainfall was procured from the different main weather stations along the length of Cameroon, from Kribi to Maroua, and computed to derive the average, standard deviation and coefficient of variation. The data are rainfall averages which rely on historical information collected over 30 years, from 1990 to 2020.

Since in Cameroon, no single meridian traverses all regions, it was difficult to select the ideal one. However, for the main criteria used in the selection of the choice longitude was breadth of geopolitical area. This means that the central longitude traversing through the most number of regions was considered. It is Longitude 14^{o}25'E. As such, in order to ensure authenticity in my findings by minimizing deviation from the meridional course to the most possible extent without compromising general accuracy, only data from the regions which have Longitude 14^{o}25'E cross it or close enough to it, was considered for analysis. These regions are: South, East, Central, Adamawa (no comparatively operational weather station), North, and Far North.

Figure 2.3: Map of Cameroon to show study area (Kribi to Maroua) including position of Long 14^{o}25'N

RESULTS AND DISCUSSION

Figures 3.0, *3.1* and *3.2* below are bar graphs showing average annual rainfall variability in Garoua, Yaounde and Kribi respectively.

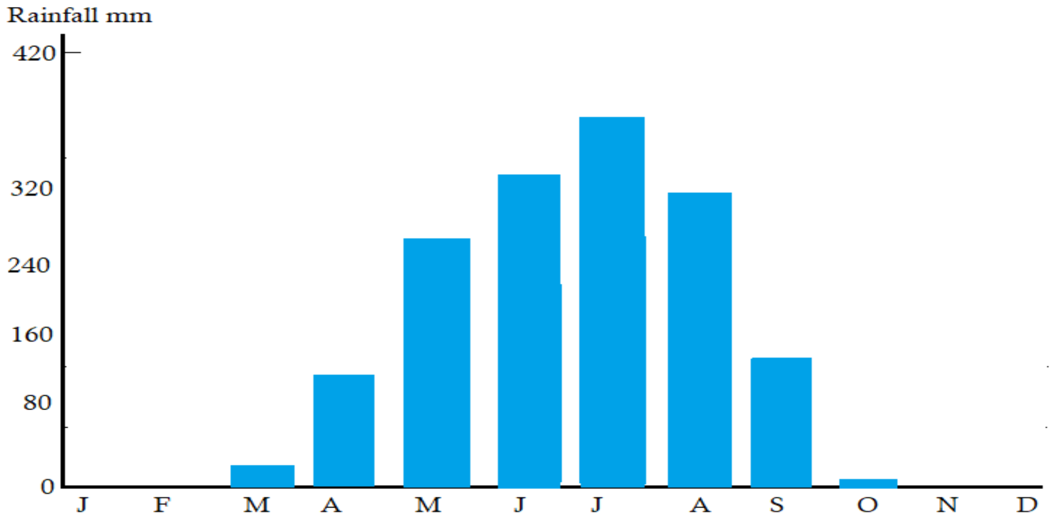

Figure 3.0: Mean annual rainfall variability in Garoua

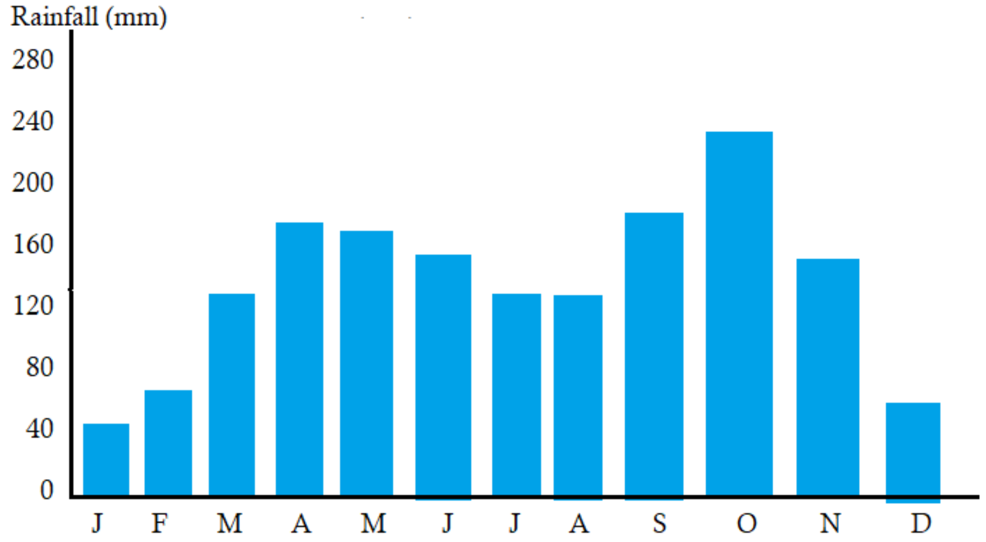

Figure 3.1: Mean annual rainfall variability in Yaounde

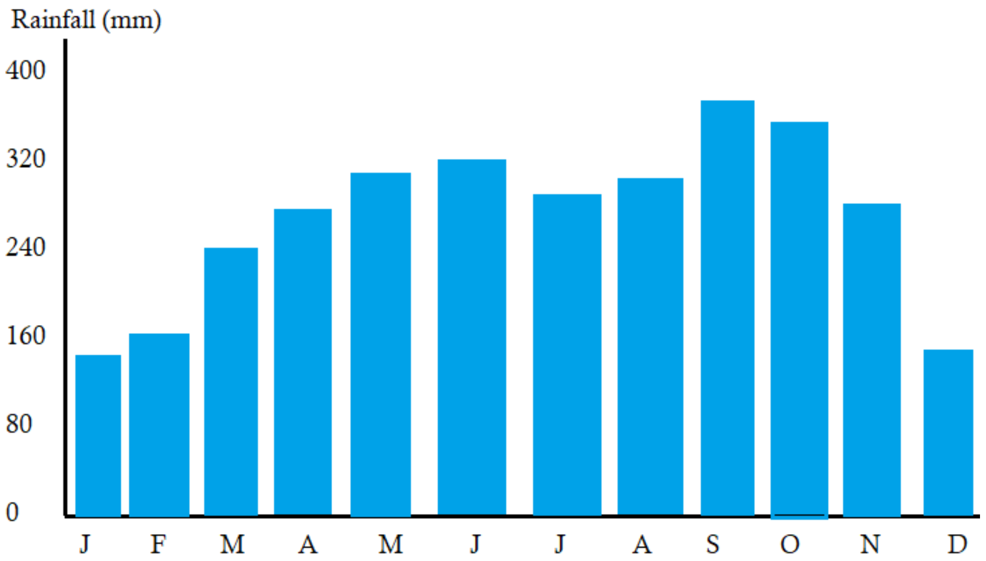

Figure 3.2: Mean annual rainfall variability in Kribi

Long-Term Rainfall Temporal Variability

Table 2.1: Summary statistics of annual rainfall (mm) of selected weather stations (1983-2021)

STATION	MINIMUM	MEDIAN	MAXIMUM	AVERAGE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
Maroua	**588.8**	**912.0**	**1587.1**	**953.5**	**261.9**	**26.6**
Garoua	**630.2**	**978.9**	**1726.7**	**1033.4**	**226.2**	**22.7**
Yaounde	**577.9**	**986.5**	**1597.8**	**1017.7**	**207.1**	**20.4**
Bertoua	**539.9**	**1024.7**	**1796.8**	**1074.1**	**271.3**	**25.7**
Kribi	**657.4**	**1115.5**	**1892.5**	**1192.5**	**218.7**	**18.8**

Statistics of annual rainfall (1983-2021) show a comparatively higher rainfall amount for all the stations. The mean annual amount of rainfall varies from 953.5 mm with a standard deviation of 261.9 at Maroua to 1192.5 mm with a standard deviation of 218.7 at Kribi. The maximum rainfall at Kribi was 1892.5 mm recorded in 2018 and the minimum was 657.4 mm recorded in 2002. In Maroua, the maximum rainfall of the period was 1587.1 mm recorded at the Maroua Salak Airport, and the minimum was 588.8 mm recorded in 1992. The result of the normality test using KS revealed non-normality in the series for all five stations at a significance of 5%. Rainfall amounts show low variability for the Kribi station (18.8%) and the Yaounde station (20.4%). Moderate variability in rainfall is observed in the rest of the stations.

Trend Of Rainfall Across The Fair Length Of Cameroon

The MK-test and Sen's slope had been calculated for the trend analyses on the long period of rainfall data from 1983 to 2021 for the five main meteorological stations in Cameroon. The results of trend analyses by the MK-test for the study stations were displayed in *table 2.1*. In the Mann Kendall trend test, a p-value less than 0.05 means a significant trend and a p-value greater than 0.05 means it is considered insignificant or simply means 'no trend' (Di Leo et al., 2020; Amrhein et al., 2019). In general, all the stations showed a positive Sen's Slope (between S Slope = 3.99 and 19.67) indicating at least an increasing rainfall trend from Maroua (northern Cameroon) to Kribi (southern Cameroon) along Longitude 14º25'E. Garoua is the only station which exhibits a non-statistically significant trend (p-value of 0.345 greater than 0.05) with a positive Sen's slope value (Sen's slope = 3.99). The other stations show p-values between p=0.000 and p=0.021 ($p < 0.05$) which makes the trends statistically significant upward trend of total rainfall amount from Maroua (northern Cameroon) to Kribi (southern Cameroon) along Longitude 14º25'E. All the stations show either zero or positive values for Kendall's tau, Mann-Kendall parameter (S), Variance (S) and this is a good sign of the increasing trend of rainfall. These results agreed with the rainfall recovery trend asserted by Lalou et al. 2019; Giannini (2015); Sanogo et al. (2015) in West Africa, and with the analysis of Traore et al. (2021). With these results, I prove that there is an increasing trend of rainfall amounts across the fair length of Cameroon, from Maroua (northern Cameroon) to Kribi (southern Cameroon) along Longitude 14º25'E, significant at 99%.

Table 2.2: Mann-Kendal rainfall trend and Sen Slope for selected weather station (1983 - 2021)

STATION	KENDALL'S TAU	SEN SLOPE	*S*	Var (S)	P-value	Alpha
Maroua	**014**	**11.83**	**302**	**6832.7**	**0**	**0.05**
Garoua	**0.11**	**3.99**	**79**	**6831.7**	**0.345**	**0.05**
Yaounde	**0.46**	**12.04**	**338**	**6832.7**	**< 0.0001**	**0.05**
Bertoua	**0.58**	**19.67**	**432**	**6832.7**	**< 0.0001**	**0.05**
Kribi	**0.32**	**10.44**	**238**	**6832.7**	**0.004**	**0.05**

Precipitation Concentration Index (Pci) Analysis

The variation and distribution in seasonal rainfall signify a significant indicator to appreciate the concentration and sequential distribution of precipitation over Cameroon in a given year. Therefore, the variability and concentration of rainfall for seasonal rain was evaluated using annual PCI based on the monthly rainfall over a 39-year period (1983–2021) for the five meteorological stations in across the fair length of Cameroon from

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Maroua (northern Cameroon) to Kribi (southern Cameroon) along Longitude 14º25'E. The result shows that the rainfall at the five weathers stations falls under two classes of ***moderate*** and ***irregular*** precipitation concentration. The Kribi station with a PCI value of 15 is the only station highlighting moderate rainfall distribution. A PCI value between 16 and 20 were observed in the reminder stations denoting an irregular rainfall distribution. These results corroborate the findings of Quenum et al. (2020), who had already proven an irregularity of rainfall in the savannah zone of Sub-Saharan Africa because of its more pronounced seasonality.

Table 2.3: PCI distribution for the ten stations used during 1983 - 2021 period

PCI	**PCI range**	**Annual**
Uniform precipitation	**< 10**	**NA**
Moderate to high precipitation	**11 to 15**	**Kribi**
Irregular	**16 to 20**	**Bertoua, Yaounde, Garoua, Maroua**
Strong irregularity	**> 20**	**NA**

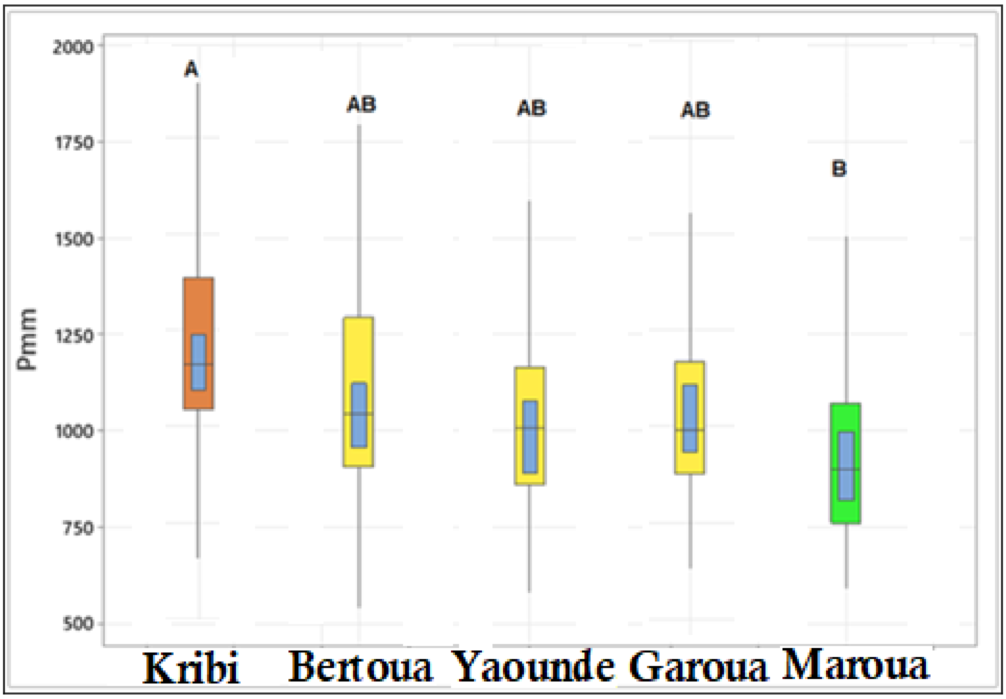

Figure 3.3: Boxplot classification of groups weather stations

Inter-Station Comparison of Rainfall

Figure 3.3 shows the result of the comparison of the rainfall series of the five main weather stations spanning the entire length of Cameroon, from Maroua (northern Cameroon) to Kribi (southern Cameroon) along the longitude 14º25'E. Two homogeneous groups of stations were obtained whose medians are different from each other. The group "A" consists of the stations of Kribi with a long-term average rainfall of around 3500 mm with a standard deviation of 253. The group "B" consists of Maroua with a long-term average rainfall of around 971mm with a standard deviation of 231. The stations Bertoua, Yaounde and Garoua, belong to the intermediate group "AB", which display similar characteristics to both the "A" and "B" groups with a long-term average rainfall of about 1042 mm, and with a standard deviation of 252. From this result, it is clear that there is local synchronicity between the stations. This means that an increase or decrease in rainfall in any weather station is not widespread for all reminder weather stations in the same climatic zone or even all stations in the study area.

CONCLUSION AND RECOMMENDATIONS

In this paper, an investigation of the rainfall variability and trend across Cameroon along the longitude 14º25'E was performed by the means of daily to annual rainfall dataset from 1983 to 2021. Statistical analysis including CoV, Mann-Kendall non parametric trend test and PCI were carried out in order to detect variability, possible trend and concentration in the rainfall time series data. The results not only revealed an increasing trend from north toward south, but rainfall amount showed moderate to high annual variability in the country's northern latitudes. A significant positive trend in total rainfall, nonetheless, was observed over the study time period. The PCI showed an irregular rainfall variability in general that corresponds to the characteristic of the equatorial and savannah zones. The comparison analysis used highlights a synchronicity between some weather stations. In order to improve precision and reliability of the application of the findings for practical use, increasing the number of study weather stations would be crucial. However, this research shows the importance of local level study in practical decision-making processes in agriculture and other water management programmes especially as concerns climate change adaptation.

Implications of Rainfall Variability in Cameroon: Reducing Trend Toward The North

The decline in rainfall poses a direct threat to food security in Cameroon, particularly in regions dependent on rain-fed agriculture. According to the Food and Agriculture Organization (FAO, 2020), about 70% of Cameroon's population relies on agriculture for their livelihoods. Reduced rainfall can lead to lower crop yields, which exacerbates food scarcity and increases vulnerability among rural populations. The World Bank (2018) emphasizes that erratic rainfall patterns can lead to crop failures, particularly for staple crops such as maize, cassava, and millet.

The variability and reduction in rainfall directly affect the growth cycles of crops. Many farmers in northern regions depend on traditional farming techniques that are closely aligned with seasonal rainfall patterns. As noted by Nguedia et al. (2019), the changing climate has led to shifts in planting dates and reduced productivity of key crops. This trend may force farmers to adapt by shifting to drought-resistant varieties or altering planting schedules, which could require additional education and resources.

Agriculture is a cornerstone of the Cameroonian economy, contributing significantly to GDP and employment. A decline in agricultural productivity due to reduced rainfall can have cascading effects on local economies. The International Fund for Agricultural Development (IFAD, 2019) reports that decreased agricultural output can lead to increased poverty levels, particularly among smallholder farmers who lack the financial resilience to absorb shocks. This economic strain can hinder rural development and exacerbate inequalities conditions (Sultan et al., 2019).

Reduced rainfall can also lead to environmental degradation, including soil erosion and desertification, particularly in the northern regions of Cameroon. As highlighted by the United Nations Convention to Combat Desertification (UNCCD, 2018), land degradation can reduce the land's productive capacity, further threatening agricultural sustainability. The loss of vegetation cover due to drought can also impact biodiversity and disrupt local ecosystems (Pretty et al., 2018).

Recommendations for Water Management And Agricultural Practices And Adaptation Strategies

Integrated Water Resource Management (IWRM)

Implementing Integrated Water Resource Management (IWRM) strategies is crucial for optimizing water use in agriculture. IWRM promotes the coordinated development and management of water resources, considering social, economic, and environmental factors (Global Water Partnership, 2021). This approach can help maximize water efficiency, reduce wastage, and ensure equitable access to water resources among farmers (Pretty et al., 2018).

Promotion of Drought-Resistant Crops

Encouraging the cultivation of drought-resistant crop varieties is essential for adapting to changing rainfall patterns. Research by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT, 2020) indicates that crops such as sorghum and millet are more resilient to dry conditions. Providing farmers with access to seeds and training on these varieties can enhance food security and stabilize yields.

Rainwater Harvesting Techniques

Implementing rainwater harvesting systems can mitigate the impacts of reduced rainfall. Techniques such as constructing small reservoirs or using cisterns can help capture and store rainwater for irrigation during dry spells (World Bank, 2018). This practice not only provides a reliable water source for crops but also reduces reliance on unpredictable rainfall (Pretty et al., 2018).

Soil Conservation Practices

Adopting soil conservation practices is vital for maintaining soil health and productivity in the face of reduced rainfall. Techniques such as agroforestry, cover cropping, and no-till farming can enhance soil moisture retention and reduce erosion (FAO, 2020). Educating farmers about these practices can contribute to sustainable agricultural development and resilience against climate variability.

Capacity Building and Farmer Education

Investing in farmer education and capacity building is critical for adapting to changing climatic conditions. Extension services should focus on providing farmers with information on climate-smart agricultural practices, water management techniques, and crop diversification strategies (IFAD, 2019). Empowering farmers with knowledge will enable them to make informed decisions that enhance their resilience (Sultan et al., 2019).

In conclusion, the trend of reducing rainfall from Kribi (South Region) to Maroua (Far North Region) presents significant challenges for agriculture in Cameroon. The implications for food security, crop yields, economic stability, and environmental sustainability are profound. However, through strategic water management practices, the promotion of drought-resistant crops, rainwater harvesting techniques, soil conservation methods, and farmer education initiatives, it is possible to mitigate these impacts. By adopting a proactive approach to agricultural adaptation, Cameroonians can work towards ensuring food security and sustainable development in the face of changing climatic conditions.

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