UNIVERSITY OF CAPE COAST

INVESTIGATING THE DYNAMICS AND DRIVERS OF EXTREME RAINFALL IN GHANA

REBECCA BERKOH-OFORIWAA

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BY

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Thesis submitted to the Department of Physics of the School of Physical Sciences, College of Agriculture and Natural Sciences, University of Cape Coast, in partial fulfilment of the requirements for the award of Master of Philosophy degree in Physics

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DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature: .... Date: ....…

Name: Rebecca Berkoh-Oforiwaa

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

Principal Supervisor's Signature: .... Date: 15-07-2019

Name: Dr. Mrs. Nana Ama Browne Klutse

Co-Supervisor's Signature: .... 15/7/19 Date: 15-07-2019

Name: Mr. David Cudjoe Adukpo

ABSTRACT

Daily rainfall data from Ghana Meteorological Agency (GMet) rain gauge network was analysed to identify extreme rainfall events in Ghana. The data was first processed in order to remove all errors in the observational time series prior to analysis. The data was then analysed by excluding all rainfall events, which fell below a pre-determined threshold in order to identify extreme rainfall event days and non-extreme event days. Inter-annual variability and trends of annual precipitation totals in Ghana are analyzed considering different gridded observational and ERA-Interim re-analysis products. The spatial and temporal distribution of the different rainfall seasons (wet and dry) over Ghana was analyzed in the period 1988-2014. The total annual precipitation as well as extreme precipitation showed a general shift towards a wet climate in the study area. Most of the variables analysed, specific humidity and horizontal moisture flux during extreme and non-extreme events showed significant differences. These are the key variables when describing climatological differences between extremes and non-extremes. The surface specific humidity distribution has relatively higher values during extreme events than the non-extreme events. The transport of moisture flux along the boundary layer at 850 hPa shows a more westward transport in wet seasons. The extreme events are favoured by southwesterly wind flow and stronger northeasterly winds as compared with the non-extreme events.

KEY WORDS

ERA-Interim re-analysis

Extreme rainfall

Inter-annual variability

Moisture flux

Specific humidity

Wind speed

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Finally, my sincere gratitude goes to God Almighty for making this project a success.

DEDICATION

To Mrs. Margaret Nti-Berkoh

For her advice, her patience, and her faith. Because she always understood.

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LIST OF ACRONYMS

AEJ	African Easterly Jet
AEWs	African Easterly Waves
AMJ	April, May, June
CDO	Climate Data Operators
DJF	December, January, February
ECMWF	European Centre for Medium-Range Weather Forecasts
GCMs	Global Climate Models
GMet	Ghana Meteorological Agency
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
ITD	Inter-Tropical Discontinuity
MoFA	Ministry of Food and Agriculture
NetCDF4	Network Common Data Form
NA	Not Available
SON	September, October, November
SSA	Sub Saharan African
TEJ	Tropical Easterly Jet

CHAPTER ONE

INTRODUCTION

Extreme rainfall events are one of the serious challenges society will have to face with a changing climate. Ghana has witnessed many colossal disasters initiated by extreme rainfall events in recent times causing immense human and economic losses. Though the phenomenon is hitting Ghana severely each year, there has been inadequate research on this subject. Insufficient networks, sparse coverage of rain gauges and Automatic Weather Stations across the country are the major factors responsible for making the prediction and observation of rainfall incredibly difficult in the region. The latest advancements in meteorological satellites and improved precipitation estimation algorithms have facilitated the research on such a subject. This study aims at studying the extreme rainfall events in a detailed manner over Ghana using ERA-Interim reanalysis precipitation. The primary focus is examining the spatiotemporal trend of extreme rainfall events over the study area. Additionally, this research also seeks to find out the relation between surface specific humidity, zonal moisture flux and atmospheric circulation at different pressure levels with extreme rainfall events. It is noteworthy that this analysis does aim at exploring the physical mechanisms responsible for extreme rainfall events.

Background to the Study

Concerns of increases in the frequency and/or intensity of climate extremes have been high across the world (Solomon, Qin, Manning, Chen, et al., 2007). Knowledge on the dynamics of these increase in frequency and intensity will give the world a leap in predicting extreme climate events and also put measures in place to lessen the effects. Many countries have experienced extreme rainfall impacts and these impacts are getting worse under climate change (Anderson & Bausch, 2006). Extreme rainfall events may occur in the form of flooding that result from longer duration of rainfall or drought as a consequence of the absence of rainfall for a longer period of time to cause crop failure (see Figure 1). After the occurrence of the 1981 – 1983 drought over most countries in the northern hemisphere, extreme rainfall events have gained much attention from the research community putting in efforts to understand the dynamics of these occurrences. Early forecasting of floods or drought still remains a challenge since it is one of the meteorological phenomena whose physics is not wholly comprehended. When these objectives of the research society are achieved, the world will be in an advantageous position to lessen the effect of these extreme events by enhancing decision making in the various sectors that are being affected by these events. In West Africa, rainfall extremes are the predominant drivers of flood and drought. Floods have been rampant in recent years in Ghana and impacted on agriculture. Agriculture is a source of livelihood in Ghana, engaging an estimate of 70% of its citizens and resulting as one of the major sources of revenue (Kyeremeh, 2016). A large number of agricultural activities in Ghana are on small scale farming and therefore any negative impact significantly does affect the economy (Kwarase, 2017). The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), released in 2007, predicts that by 2050, yields from rain-fed agriculture in some Sub Saharan African (SSA) countries could be reduced by up to 50% due to climate change.

Figure 1: Crop failure due to Drought event in Bolgatanga in 2006.

Source: Kankam-Yeboah, K., Amisigo, B., & Obuobi, E. (2011)

The climate of Ghana and rainfall characteristics

Ghana is situated in the northern hemisphere with latitude ranging between 4.5 ^{o}N and 11.5 ^{o}N, and Longitude between 3.5 ^{o}W and 1.3 ^{o}E sharing borders with Cote d'Ivoire to the west, Togo to the east, Burkina Faso to the north, and to the south the Gulf of Guinea and the Atlantic Ocean. Ghana is represented by sixteen regions with 22 synoptic weather stations by Ghana Meteorological Agency. The topography is predominantly undulating and of low relief with slopes of less than 1%. Factors influencing the climate experienced in Ghana include; altitude, the proximity of the water bodies, the migration of the Inter-Tropical Convergence Zone (ITCZ) and the location of dominant atmospheric high and low-pressure systems. The weather in this region is controlled by the movement of the ITCZ, which is a belt of low pressure mostly close to the equator as the Northern and Southern hemispheres coincide. The south-westerly wind is the most prevailing wind in the south of the ITCZ blowing from the Atlantic Ocean to the continent, whilst in the north of the ITCZ, the predominate wind migrates from northeast carrying with its warmth and dust air from the Sahara Desert. Year-round, the ITCZ is found, moving to and fro the southern hemisphere into the northern hemisphere thereby inducing dry and wet seasons. The Southern part of Ghana is characterised by mainly two rainy seasons, first rainfall season is from April to June (AMJ) and the second rainfall season from September to November (SON) whilst the Northern part experience a unimodal rainfall season in April and reaches its maximum in August-September. Annually the rainfall varies from about 1,100 mm in the north to about 2,100 mm in the southeast. A dry wind known as harmattan blows from the northeast in the month of November until early March. This harmattan wind results in a decrease in the content of moisture in the air as temperatures in the day become hot whilst that of the night is cool. The transition zone experiences a much longer raining period which begins in April and reaches a relatively low maximum in June, then a steady rainfall until September.

African Easterly Waves (AEWs)

African easterly waves, are westward-traveling waves that originate over northern Africa primarily between June and October. They have approximate horizontal wavelengths of 2500 km, periods of 3 - 5 days, and move westward at a rate of 8 ms^{-1} (Diedhiou, Janicot, Viltard & de Felice, 1998). Previous theories for AEW formation suggested that they are formed in response to the breakdown of the ITCZ or the growth of instabilities associated with the African easterly jet (AEJ) Hsieh et al., 2008. Current theory, however, suggests that AEWs form in response to latent heating associated with mesoscale convective systems that form along higher terrain in eastern Africa (Quagraine, 2014; Hsieh et al., 2008). They grow at the expense of the AEJ via a combined barotropic baroclinic energy conversion process (Charney & Stern, 1962; Cornforth, Hoskins & Thorncroft, 2009). They reach their largest amplitude near the west coast of Africa and generally, decay after emerging over the eastern Atlantic Ocean 6-8 days after their formation. Largest wave amplitudes are found at approximately 650 hPa and the waves exhibit a vertical tilt against the shear vector; in other words, for easterly vertical wind shear, AEWs tilt to the east with increasing height. Substantial variability in AEW structure and evolution exists due to (a) variability in the side of the AEJ on which they form and (b) AEJ intensity and structure. AEWs, particularly those that form in moist environments south of the AEJ, serve as the primary seedling disturbances for tropical cyclone formation in the north Atlantic and eastern North Pacific Ocean basins.

Tropical Easterly Jet (TEJ)

The TEJ is an upper-tropospheric (100-200 hPa) easterly jet that extends across the tropics from the eastern Indian Ocean to western Africa Lemburg et al., (2019). The jet's latitudinal width is approximately 20 ^{o} – 30 ^{o}. Maximum wind speeds associated with the jet are on the order of 35 – 40 ms^{-1} are typically found between 5^{o} - 10^{o} North from southern India toward the east coast of Africa. The TEJ is found on the southern periphery of the upper-tropospheric anticyclone atop the Tibetan plateau associated with the Asian monsoon. Indeed, the TEJ is intricately linked to the Asian monsoon and its divergent upper-tropospheric anticyclone. The TEJ is weak when the monsoon is weak and strong when the monsoon is strong, suggesting that variability in the monsoon also modulates variability in TEJ strength (Nicholson and Grist, 2001). The jet becomes established once the monsoon has started for the season and decays once the monsoon has ended for the season; thus, it is a salient feature of the tropics only during Northern Hemisphere summer. Deep, moist convection preferentially forms in the right entrance and left exit regions of the TEJ or those in which upper-tropospheric divergence is promoted. The right entrance and left exit jet regions are typically located over Southeast Asia to the northeastern Indian Ocean and central to western Africa, respectively. The right entrance region of the jet corresponds with the upward branch of the Walker circulation that extends from Southeast Asia eastward across the Pacific Ocean. Variability in TEJ structure, intensity, and location can impact deep, moist convection initiation (Lemburg, Bader & Claussen, 2019).

African Easterly Jet (AEJ)

The AEJ is a middle tropospheric jet located over much of tropical northern Africa during Northern Hemisphere summer. The AEJ has maximum (climatological) easterly wind speeds of greater than 15 ms^{-1} ($\approx$ 10 – 12 ms^{-1}) along 10 ^{o} – 15 ^{o} North between 700-600 hPa. It exhibits large vertical and horizontal wind shears (Skinner & Diffenbaugh, 2013). The vertical wind shear associated with the AEJ is crucial to deep, moist convection organization and squall line initiation. Both horizontal and vertical wind shears are important for AEW growth via barotropic and baroclinic instability (Wu, Reale, Schubert, Suarez & Thorncroft, 2012). AEWs grow at the expense of the AEJ, or, put another way, AEJ strength is modulated (i.e. weakened) by AEWs. The AEJ plays a crucial role in the West African monsoon system and is largely in geostrophic balance. The AEJ is associated with a geostrophic circulation that enhances upward motion and deep convection south of the jet and downward motion along and north of the jet. AEJ is maintained by two separates adiabatically forced meridional circulations (Thorncroft & Blackburn, 1999). The first, associated with dry convection in the Sahara, is characterized by the contrast in sensible heating between the warm, dry Saharan air over northern Africa and cooler, moister air at equatorial latitudes. This contrast results in a positive meridional potential temperature gradient that brings forth the strongly vertically sheared easterly zonal wind between 850-650 hPa associated with the AEJ. The second is associated with deep, moist convection that leads to upper tropospheric heating equator ward of the AEJ. The observed upper-tropospheric westerly vertical wind shear with the AEJ results from the reversal of the meridional potential temperature gradient associated with this heating at equatorial latitudes. Significant intraseasonal and interseasonal variability in the AEJ exists due to rainfall variability across northern Africa. Reduced precipitation reduces soil moisture content across the southern Sahara and northern Sahel regions of North Africa, permitting stronger near-surface sensible heating and thus deeper mixed layers. The AEJ tends to be stronger when sensible heating is strongest and mixed layers are deepest over these regions. Such conditions lead to an enhanced meridional temperature gradient (and, subsequently, stronger AEJ) between the Sahara and equatorial regions of Africa. The AEJ tends to be weaker when sensible heating is weak and mixed layers are shallow, thus weakening the meridional temperature gradient (and, subsequently, AEJ) across northern Africa.

Moisture flux and moisture transport

Moisture is a representation of water vapour content in the air. Water vapour leading to the formation of precipitation results from evapotranspiration and moisture flux or transport (Wicaksono & Hidayat, 2016). Heavy rainfall is experienced when water vapour is continuously transported into a sink region from outside. Water vapour present in rain-bearing clouds which are responsible for all kinds of precipitation, and the amount of water vapour present in a given volume of air indicates the atmosphere's potential capacity for precipitation. The amount of water vapour also decides the quantity of latent energy stored up in the atmosphere for the development of storms and cyclones. Therefore, measurement and knowledge of atmospheric water vapour are essential for the prediction of weather elements like cloud, fog, temperature, humidity and precipitation.

Flood events in Ghana

Rainfall in Ghana is regulated by two wind systems; one originating from the Sahara Desert known as the northeasterly winds and the other from Atlantic Ocean southwesterly winds. The boundary of these two air masses is called the Intertropical Discontinuity (Ofori-Sarpong, 1983; Pospichal et al., 2009). Ghana suffered flooding in 1968, which displaced 25,000 of the populaces with a lot of properties destroyed (Asumadu-Sarkodie, Owusu, & Jayaweera, 2015). Nevertheless, Ghana in 1991 faced an event of drought as a result of El Nino leading to the poor performance of crops (FAO, 2014). In July 1995, there was a massive flood in Accra and some towns in close vicinity to Accra which led to 30 lives lost and 50 billion Ghana Cedis (GHS) worth of properties (Danquah, 2013). In August and mid-September 2007, the northern part of Ghana experienced a downpour, which led to the destruction of infrastructure, loss of lives and loss of crops leading to food insecurity (Armah, Yawson, Yengoh, Odoi, & Afrifa, 2010). June 2009, the capital of Ghana was affected by a heavy flood that led to loss of lives and damage of valuable properties (Kankam-Yeboah et al., 2011).

Statement of the Problem

Extreme rainfall has been a great nuisance to society in the past and recent years. This has resulted in the destruction of properties and loss of lives, as it results in flooding due to the inability of drainage systems to hold up excess water. Also, drought which is as a result of deficit of water leading to crop failure and electric power crisis as Ghana relies of hydro-power. Ghana as a whole suffered insufficient power supply due to a drought event in 2006 since the country relies on hydro-power (Kankam-Yeboah et al., 2011). Also, future rainfall can result in severe destruction if drainage systems are unable to hold up excess water. Figure 2 shows a street flooding event in Accra on 23rd April 2008. Northern Ghana experienced a heavy rainfall event in August 2007 affecting 350,000 populace and claiming the lives of 49 people with estimated damage worth 130,000,000 United States Dollars (US$) (Asumadu-Sarkodie, Owusu, & Rufangura, 2015).

Figure 2: Overflow due to an Extreme Rainfall Event in Accra in 2008.

Source: (Kankam-Yeboah et al., 2011).

The outcome of heavy rains has left many farmlands inaccessible due to damage to roads and bridges linking the farmland and settlement areas, leading to food shortage (Armah et al, 2010).

Information obtained from extreme rainfall is often employed in the designing and construction of vital facilities such as reservoirs dams, urban runoff. This event and identical ones have stirred discussions to determine which measures should be observed during such occurrences. Hence, a good estimation of extreme precipitation will boost the economy and guarantee safety. Extreme precipitation is evidence of climate change (Fosu-Mensah, Vlek, & MacCarthy, 2012; Gyampoh, Amisah, Idinoba, Nkem, & others, 2009; Laube, Schraven, & Awo, 2012; Waylen & Owusu, 2014). Temperatures are observed to be changing globally as a consequence of human activities leading to high greenhouse gas emission (McCarty, Canziani, Leary, Dokken, & White, 2001). Rising temperature has become a global threat to the hydrological cycle resulting in more frequent extreme dry and wet occurrence adversely affecting small scale farming and food security.

Global Climate Models (GCMs) have been used by Scientists to quantify the projections of future temperature changes (Semenov & Stratonovitch, 2010; Liang, Kunkel, Meehl, Jones & Wang, 2008). Researchers can estimate the discharge and rainfall, which then can be used in the design of hydraulic systems. Therefore, an accurate approximation of rainfall amount and runoff will help alleviate most rainfall related hazards. This thesis is centred on some key statistics and dynamics of extreme rainfall for twenty-two weather stations in Ghana. These statistics and dynamics will be geared towards scientific understanding and also improving agriculture policies.

Purpose of the study

The main purpose of this work is to identify the underlying factors that influence precipitation resulting in extreme rainfall events over Ghana.

Research objectives

Recent studies are focused on the need to investigate the climatic variable influencing climate change, which happens to be a motivating factor for conducting this project. This work focuses on:

i. Analysing seasonal and spatial characteristics of rainfall.

ii. Investigating the trends of extreme rainfall.

iii. Investigating the drivers of extreme rainfall events.

Research questions

The following research questions illustrate the aspects of the research objectives pursued:

i. Are there any trends in the occurrence of extreme events?

ii. What are the drivers of extreme events?

Significance of the Study

The effect of extreme climate has been an issue of concern lately in Ghana due to the frequent flooding situation happening in some parts of the country. The findings of this study will therefore contribute significantly to academia by providing information on the climatic factors driving the extreme rainfall events. The findings will also provide a database to aid policy makers in making decision regarding extreme rainfall events. Again, the findings of the study will help also to provide information for stakeholders of agriculture.

Delimitations

Geographically, the study was conducted over Ghana. All figures are presented in national scope and do not provide information about trends in extreme or heavy precipitation on a local or regional scale. The atmospheric circulation variables included in this study are limited to only surface variables like specific humidity, zonal moisture flux and also excludes the effect of teleconnections on extreme rainfall.

Limitations

The extreme events considered in the study do not represent all possible extreme events influenced by climate factors. The extreme events defined are not solely dependent on atmospheric or meteorological quantities like rainfall. The section on extreme precipitation, a meteorological event, considers only rainfall, not flooding, as the defining characteristic.

Organisation of the Study

This thesis consists of five main chapters. Chapter 2 summarizes the literature available on extreme precipitation and related factors. Chapter 3 describes the study region, the datasets and methodology adopted for this research. Chapter 4 discusses the results obtained. Chapter 5 summaries the findings, give conclusions regarding the research objectives.

Chapter Summary

In this chapter, Extreme rainfall event was discussed alongside with the history of the occurrence of flood events in Ghana. Also, the drivers of rainfall over West Africa which are African Easterly Jet, Tropical Easterly Jet, Moisture Flux was discussed as well as the importance and limitations of the research.

CHAPTER TWO

LITERATURE REVIEW

Introduction

This chapter provides an overview of research work carried out on the measures of extreme rainfall events and drivers. A background is also provided on the climate and climate change with a focus on the important circulations that affect climate.

Extreme rainfall trends and drivers

An analysis of extreme precipitation events shows that their frequency has increased significantly in the United State since the 1920s/1930s (Shang, Yan, Gebremichael, & Ayalew, 2011). There has been no noticeable pattern in the frequency of the most extreme events in Canada, but the frequency of less extreme events has increased in some parts of Canada, particularly in the Arctic (Kunkel, 2003). (Wang et al., 2012) conducted research finding that the mean annual precipitation over southwest, northwest and east China has increased significantly while that of central, northeast China has dropped significantly. Increasing rainfall over Katulampa is contributed to by Madden-Julian Oscillation and cold surge (Wicaksono & Hidayat, 2016), which modifies the transport of water vapor resulting in the formation of convective clouds over Java Island with a time lag of about 1 to 2 days. Also, rainfall magnitudes can also be characterized by Outgoing Longwave Radiation. Most of the extreme precipitation events occurring in Western Europe and the western United States are associated with low-level winter jets and atmospheric river events. For South America, extreme precipitation is associated with low-level jets. It has been identified that both atmospheric moisture transport and soil moisture (Wei, Su, & Yang, 2016) may influence precipitation over the southern United State. The occurrence of more extreme precipitation in the upper Yangtze River Valley was found to be the result of the weakening of the summer monsoon trough of the South China Sea, the intensification of Eurasian-Pacific blocking highs, an intensified South Asian high, a south subtropical Western jet and an intensified Western North Pacific Subtropical resulting in increased atmospheric instability (Tian & Fan, 2013). There has been a decrease in the average total precipitation over South and West Africa, this decrease is said to be statistically insignificant (New et al., 2006). The average regional rainfall intensity over South and West Africa has increased significantly over the period 1961-2000 with an increasing trend (New et al., 2006). (Easterling et al., 2000) also found that there were significant increases in heavy rainfall days per year in southwestern South Africa for the period 1926 to 1997 and in the KwaZulu-Natal domain for the period 1901 to 1997. (Groisman et al., 2005) found that there was no significant change in the total annual and summer precipitation for the eastern part of South Africa between 1906 and 1997, but there was a significant increase in the annual frequency of very heavy precipitation. Also, (Mason, Waylen, Mimmack, Rajaratnam, & Harrison, 1999) found no significant trend in annual rainfall over South Africa. Both low-level jets and atmospheric rivers were involved in flooding events in subtropical southern Africa (Gimeno et al., 2016). Therefore, low-level moisture flux at 850 hPa contributes to rainfall over West Africa during April–June, the northern flux forms a "moisture river" that carries the moisture current to the Gulf of Guinea (Lélé, Leslie, & Lamb, 2015). Southward transport is weakening in July-

September as the monsoon peaks, but westward transport is expanding and extending to 20^{o} North responsible for strengthening the West African jet off the west coast. The Sahel region is mostly affected by the zonal component of moisture, while the southern transport influences the coast of Guinea (Lélé et al., 2015).

Defining extreme climate

Extreme weather leads to questions as to whether such events have varied in frequency or intensity over time. A fundamental understanding of an extreme event focuses on the hypothesis that there is a "normal" state generally derived from a time series of conditions observed. Many climate attributes are well represented by monthly mean, with most indices generally focused on extremes derived from daily data. Figure 4 shows a representation of extreme. Extreme has been used in a number of climate-extreme scientific literatures referring to occurrences with a daily maximum exceeding a certain percentile value (threshold) of daily variability as estimated from a climate base period or may refer to rare occurrences in the far tails of the distribution phenomenon of interest (Peterson, Stott, & Herring, 2012). Extremes are well understood in a circumstance and therefore seasonal or annual means can be “extreme” just as a unique short-term event can be extreme, such as a daily amount of precipitation. Therefore, a deviation from the mean with a low frequency of occurrence would also define an extreme event. (Dankers & Hiederer, 2008) did define an extreme event as "Extreme climatic events for a particular ecosystem are statistically rare in frequency, magnitude, and/or duration for a single climatic parameter or combination of parameters”. The length of reliable observational records depends on the ability to recognize and categorize extreme events. An extreme climate event may or may not induce an environmentally friendly response. Extreme events can also be defined on the basis of the impact on society or the environment, such as loss of human life, economic loss, property damage, and others, (Easterling et al., 2000). Figure 3 shows how it would be expected that the frequency distribution of an observed climate parameter would vary around a mean value over a period of time and for a given point or area. There are three main characteristics of extreme events: thresholds (minimum / maximum), frequency and magnitude.

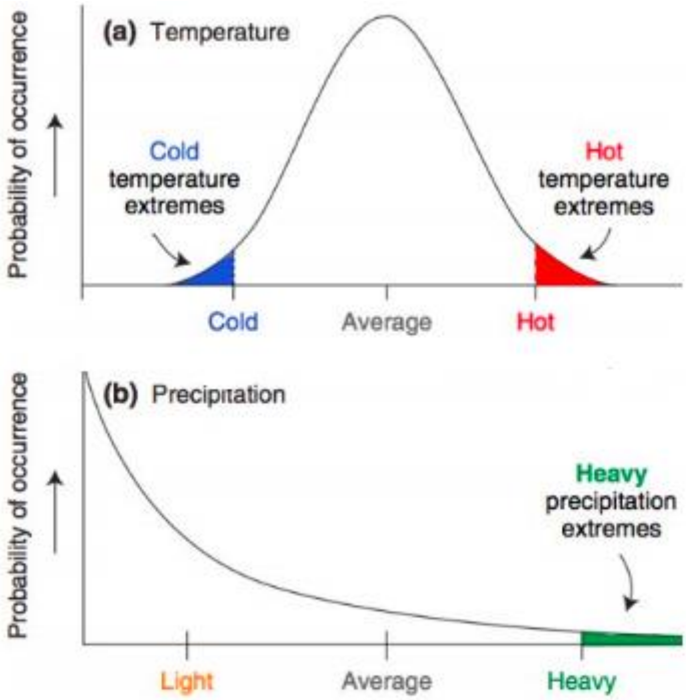

Figure 3: Daily Temperature and Precipitation distributions of probability; the higher the black line, the more frequently the weather with these characteristics occur. The shaded areas denote Extremes

Source: Zhang et al., 2011.

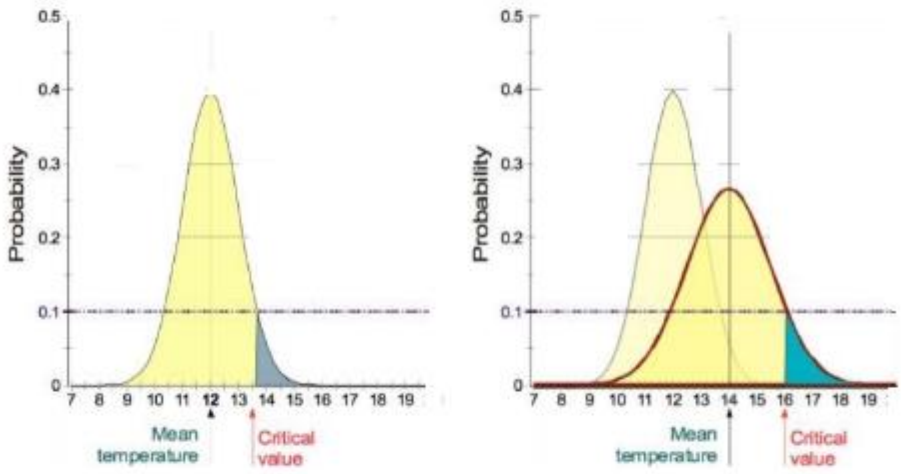

Figure 4: Idealized frequency distribution for event and distribution shift.

Source: Dankers & Hiederer, 2008.

95th percentile for an extreme rainfall event

A large amount of the available scientific literature on climate extremes is based on the use of' extreme indices, which can be either probability-based or threshold-based. Indeed, both from a probability and threshold perspective, hazards to society and ecosystems are often considered extreme in scientific literature, with several other aspects considered in the definition of extreme rainfall for a given time frame (days, month, season, annual). The 95th percentile is generally defined in relation to a reference time period. Other definitions relate, for example, to the number of days above specific absolute thresholds of precipitation or to more complex definitions of the length or persistence of extreme climatic conditions. Some of the advantages of using predefined extreme indices are that they permit some comparability across modeling and observational studies and regions. In addition, in the case of observations, it may be easier to obtain derived indices than in the case of daily precipitation data, which are not always distributed by meteorological services. An extreme is not defined accurately.

Observed and projected changes in extreme events

Land use and burning of fossil fuel was one of the main activities that increased the number of greenhouse gases in the atmosphere of the earth. An increase in the quantity of these greenhouse gases thus increases the heat content of the earth's atmosphere, usually by absorbing outgoing radiation which would have been radiated into space. This heat increase has led to the greenhouse effect, which has led to climate change. The main characteristics of climate change are increases in average global warming; changes in cloud coverage and precipitation especially on land; melting of ice caps and glaciers and reduced snow cover; and increases in ocean temperatures and ocean acidity due to seawater that absorbs heat and carbon dioxide from the atmosphere. The Intergovernmental Panel on Climate Change confirms that the climate is changing over time (Solomon et al., 2007). Climate change is due to global temperature change mainly due to anthropogenic activities (CO_2) resulting to the increase in greenhouse gas emissions. Inter-Governmental Panel on Climate Change has shown that the earth temperature has increased by 0.74 °C between 1906 and 2005 due to increase in anthropogenic emissions of greenhouse gas (Solomon et al., 2007). Predictions by 2100 global average temperature is expected to increase as much as 4 ^{o}C rise (Mejia, Mrkaic, Novta, Pugacheva, & Topalova, 2018). Similar can be found in Figure 5. For centuries, human beings have adapted to the variable climate around them. Regional climate variability can shape policies to improve lives and livelihoods with regard to social, economic, political and personal conditions. The disadvantages of the changing climate indicate that the climate variability known to civilization has changed and continues to change at a relatively rapid rate. Global warming's biggest impacts and threats are widespread. Increasing ocean temperatures cause ocean thermal expansion and this causes sea level rise in combination with melt water from land-based ice. Over the 20th century, sea levels rose by 0.17 m. It is expected that sea level will rise between 0.18 and 0.59 m by 2100. Due to uncertainty about how much water will be lost from ice sheets, there are uncertainties in this estimate (Bindoff et al., 2007). Increased melting of sea ice and freshwater flow from melting glaciers and ice sheets also has the potential to influence ocean circulation patterns worldwide. The type, frequency and intensity of extreme events such as tropical cyclones, floods, droughts, and heavy precipitation events are expected to increase as a result of global warming, even with relatively small average temperature increases. Changes have already been observed in certain types of extreme events. The rise in climate change has a negative impact on all sectors of the earth and will continue to do so. Rising temperatures will cause crop seasonal shifts that affect food security and changes in disease vector distribution that put more people at risk from diseases like malaria and dengue fever. Increases in temperature may significantly increase extinction rates for many habitats and species. An increase in extreme events will have health and life effects as well as associated environmental and economic impacts that will require different adaptation policies in the future including early warning systems for extreme events, improved water management, improved risk management, various insurance options, and conservation of biodiversity.

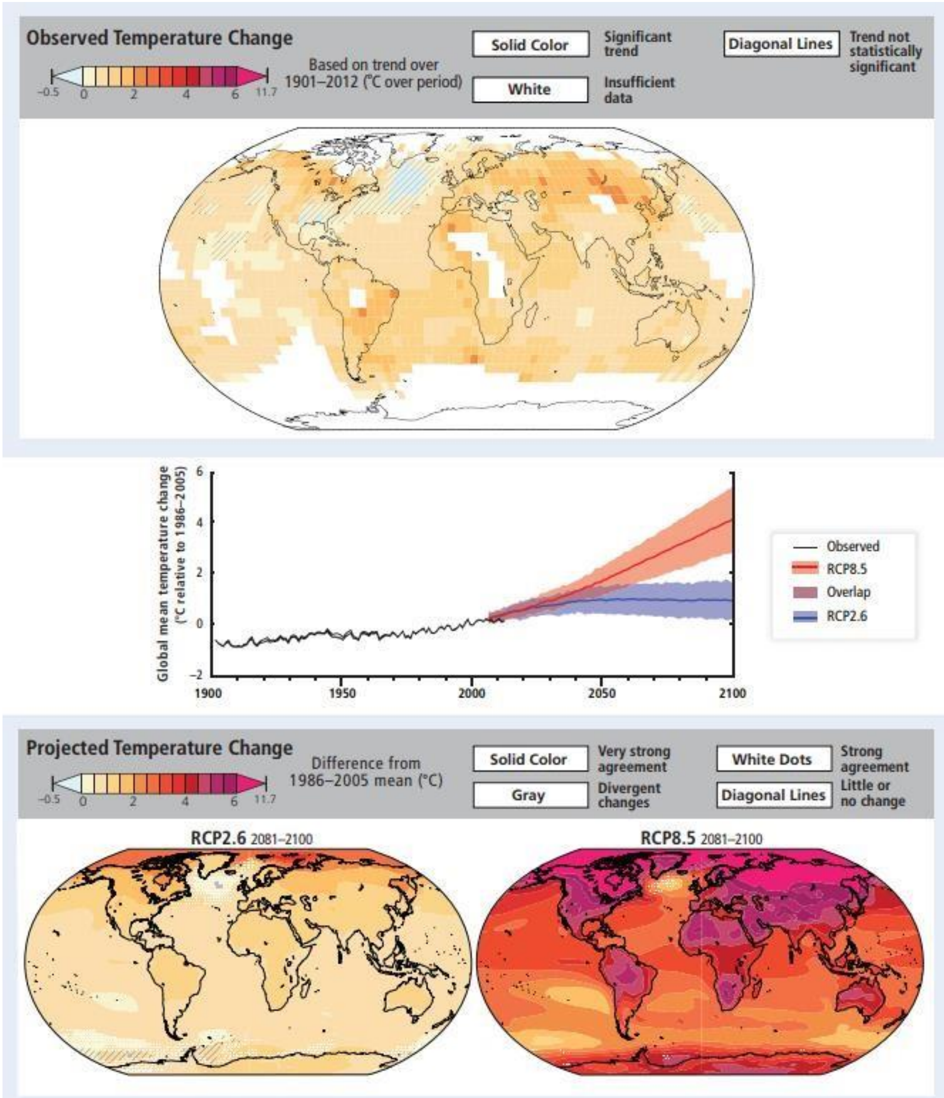

Figure 5: Observed and projected changes in Annual Average surface Temperature. This figure informs understanding of Climate-related risks in the Working Group II contribution to the IPCC's Fifth Assessment Report. It illustrates Temperature change observed to date and Projected Warming under continued high emissions and under ambitious mitigation.

Source: Field et al., 2014.

Chapter summary

In summary this chapter reviewed existing literature and knowledge in the field. It provides a basis for the discussions on climate change and extreme events. It is not intended to present a full account of the field of study, but rather the necessary facts to familiarise the reader with the context in which the investigations were performed.

CHAPTER THREE

RESEARCH METHODS

Introduction

This chapter provides a description of the data and methods used in the study. It begins with a concise description of the observational and reanalysis data used in the study. A description of the main domain of the study. Finally, a description of the techniques used in the core analyses is provided.

Atmospheric Reanalysis Data

Atmospheric reanalysis is considered to be the best estimate of the historical state of the Earth's atmosphere. The data used to analyse the antecedent atmospheric conditions to extreme events was a global atmospheric 6-hourly reanalysis data product collected from ERA-Interim by European Centre for Medium-Range Weather Forecasts (ECMWF) for 27 years from 1988 to 2014. Data for precipitation, meridional and zonal wind component at three pressure levels, 850 hPa, 700 hPa, and 200 hPa were considered for this study as these levels are known to influence the climate of West Africa (Philippon, Reyes, & Ruti, 2009). Also, surface specific humidity, as well as specific humidity at 850 hPa was utilized for analyzing moisture flux calculated from equation (3). ERA-Interim is a global atmospheric reanalysis produced by the ECMWF, covering the period since 1989 (Dee & Uppala, 2009). The ERA-Interim project is a substitute for previous atmospheric reanalysis ERA-Interim. Era-Interim project focuses on rectifying some issues with the older version ERA-15, ERA-Interim such as the hydrological cycle, the quality of the stratospheric circulation, and contamination of climate signals by changes in the observing system (Dee & Uppala, 2009). The ERA-

Interim data assimilation system is described in more detail by (Simmons, Uppala, Dee, & Kobayashi, 2007). Era-Interim has a 3 – hourly time step Gridded data products for accounting for land surface and ocean-wave parameters and 6 – hour time step for air parameter ranging from the troposphere to the stratosphere. The ERA-Interim data used in this study are daily means based on four successive 0 to 24 hour forecasts with a grid resolution of 0.75^{o} x 0.75^{o} obtained from the ECMWF data server.

Rain gauge observation

Daily rain gauge data is used from twenty-two weather stations in Ghana. The daily precipitation observations were obtained from Ghana Meteorological Agency (GMet). Most of the meteorological stations provide daily routine synoptic information. Therefore, each observation is viewed as a data point describing the instantaneous weather conditions at that location. Taking into consideration the need for having as long as possible consistent time series for all twenty-two weather stations of which the location is shown in Figure 6. A period from 1988 until 2014 was chosen due to coherent time series for all stations, which can be easily compared and simultaneously analysed.

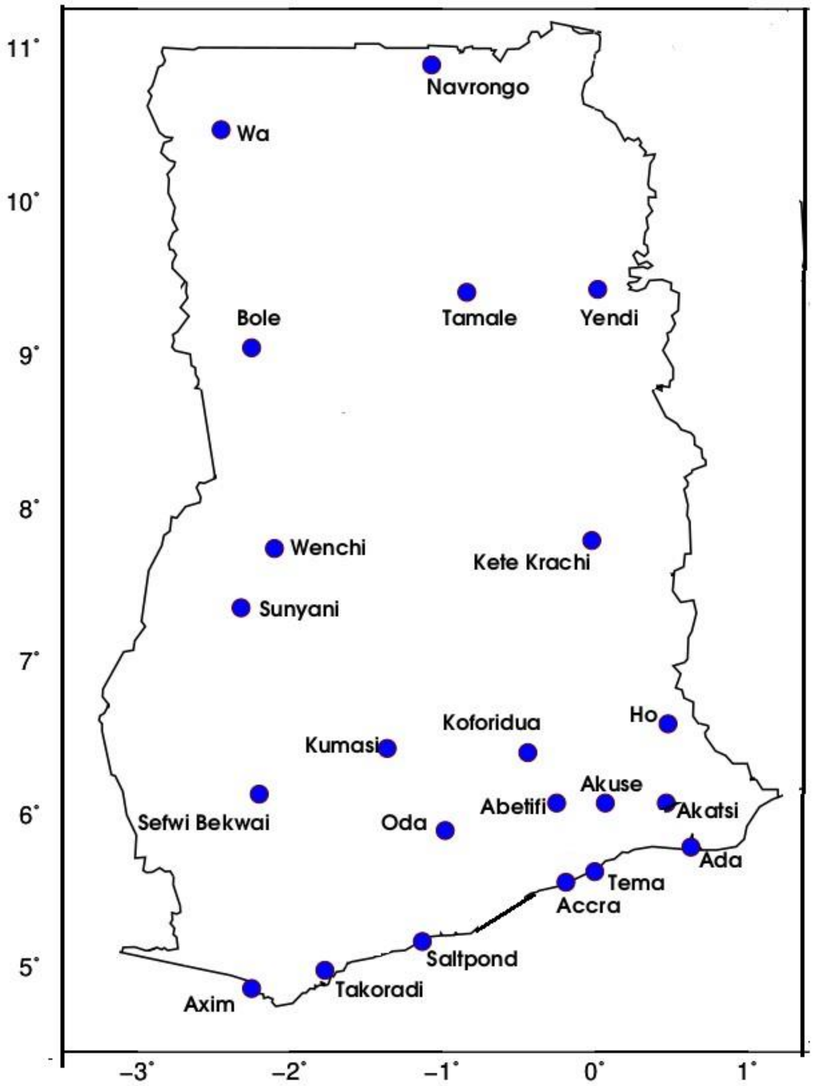

Figure 6: A map of Ghana showing the locations of the 22 weather.

Quality Control of Station data

The station data daily was checked for quality control as there might be a change in the location of station, environment change around the vicinity of the station, the type of observation instrument and the change of observation time thus directly affect the continuity of the observation dataset and have the different degrees of influence on the uniformity of annual climate data sequence. However, it is necessary to select qualified observation data by carrying out quality control on the dataset before analysis in order to ensure the accuracy of the results of the study. Quality control of meteorological ground-based data in this study was checked for precipitation less than 0 and also flagging out potential incorrect data defined as values exceeding a certain threshold, also time series plots were generated to visualise the dataset. Outliers from the time series with standard deviation of 3σ for precipitation were flagged as potential errors. The outliers refer to the values that the daily data records are more than user custom range. Potential errors were validated with those values that were confirmed to be erroneous set as missing and deleted from further analysis. The software used to carry out Quality control is called RClimdex. The input file suitable for RClimdex should be in a defined format. The initial step for quality control using RClimdex is to put the data in an ASCII text file. Then the sequence of the dataset was prepared in the required format such as six columns; Year, Month, Day, Precipitation (mm/day), maximum temperature (^{o}C) and minimum temperature (^{o}C). Also, columns should be separated by space. Missing data in the records must be filled with the value -99.9 as recognised by RClimdex as a missing value. Lastly, the data must conform to the calendar date. RClimdex software mainly includes three steps to do the quality control: (1) to modify all the missing values to the format which can be identified by the software, for example, -99.9, after automatically identifying the error of the raw data and to replace all unreasonable value to not available (NA). (2) To examine the potential outliers in the data sequence so that the researchers make a test, calibration and delete according to the actual data. In this study, the threshold of outliers is set as the daily highest temperature is not more than 45 ^{o}C the daily minimum temperature is no less than -35 ^{o}C, and the daily rainfall is not more than 180 mm. In this case of this, the study set three standard deviations to test the threshold of abnormal data so as to better determine the quality of the raw data. (3) The software will automatically generate time series diagrams of rainfall and temperature.

Software used

I. Climate Data Operators (CDO): All the initial data extraction and file handling have been done with the help of scripts written in CDO.

II. Python: A version of python known as Jupyter Notebook which has an interactive computational environment, in which you can combine code execution, rich text, mathematics, plots and rich media. It has been thoroughly used in carrying out all the data analysis and generation of plots in this project.

III. Ferret: Ferret which is an interactive computer visualization and analysis environment was also used for plot generation.

Research Methodology

In order to fulfill the discussed purposes, the following approach has been devised as depicted in Figure 7:

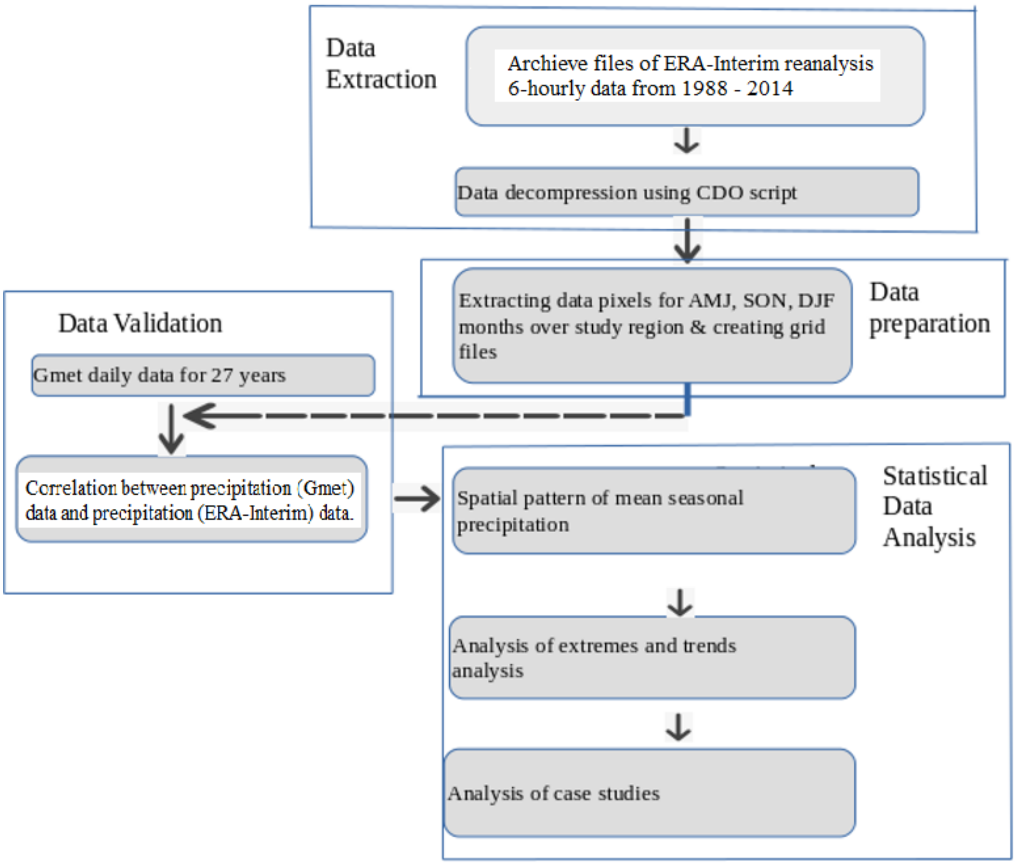

Figure 7: Research methodology adopted for this study. The steps are described in details.

Data extraction

Network Common Data Form (NetCDF4) files containing precipitation data, specific humidity, zonal and meridional winds data were downloaded in the form of archived files. A CDO script was developed to extract all the files to their respective directories. Another CDO script was generated to create a file list in text format containing the precise location of each file for further processing.

Data Preparation

A 6-hour time interval (0:00, 06:00, 12:00, 18:00) files initially came in NetCDF4 format which was then converted into daily rainfall with the use of CDO. The files were extracted only for April, May and June (AMJ), which is represented as the major rainfall season for the southern part of Ghana of which the study area lies (Owusu & Waylen, 2013). Also, similar was done September, October and November (SON) representing the minor rainfall season (Nkrumah et al., 2014) for the period 1988 - 2014.

Data validation

Satellite rainfall estimations are compared with corresponding gauge data observational dataset to identify the nature of the estimated errors. Comparison is, therefore, the assessment and quantification of the relationship between satellite-based data and observed data. These observations are known to be quantitative (Stanski, Burrows, & Wilson, 1989). The visualization or eyeball method is the primitive method for verification. This method is carried out by looking at the re-analysis and observed data side by side to determine any similarities or differences. The advantage of using the visualization method is the most effective and easy diagnostic verification with the disadvantage being that it is not quantitative (Gómez, 2007). The common way to present and visualize data is the correlational analysis as shown in Figure 8. Therefore, the first objective of this study is to validate the ERA-Interim data with ground-based precipitation measurements for the research work. In order to achieve the objective, the following analysis has been performed.

The correlation analysis has been performed to determine the bias in ERA-Interim reanalysis dataset with respect to GMet ground-based data using Karl Pearson's coefficient of correlation and scatter plot. The Pearson's coefficient of correlation denoted as R, can be calculated using the following mathematical expression:

$$R = \frac{\sum(x - x_{mean})(y - y_{mean})}{N\sigma_x\sigma_y} \quad (1)$$

x_{mean}= mean of x variable.

y_{mean}= mean of y variable.

σ_x= standard deviation of variable x

σ_y= standard deviation of variable y

N= number of pairs of observations

Statistical Data Analysis

Determining the precipitation threshold when identifying extreme events across a region is a subjective process and the choice of a sensible threshold level varies considerably depending on location. In Ghana, average annual rainfall varies markedly across the country, so it is reasonable to assume that precipitation thresholds for extremes will also vary with location. For the purpose of this study threshold for an extreme event was determined for each individual station. The threshold of extreme rainfall was determined by using the percentile method as done in (Haylock & Nicholls, 2000; Manton et al., 2001). Defining extreme rainfall by a threshold can be a difficult task and this can only be resolved by selecting an extreme event above a certain percentile, which allows the threshold to vary according to the rainfall levels in each weather station. Due to the very large number of days with low or no rainfall occurring, it was necessary to choose a high percentile threshold to prevent an excessive number of events being selected. Above 95th percentile was considered as an extreme event and below the 30th percentile as non-extremeevent for the purpose of this study. This method of extracting extreme events leads to thresholds, which are dependent on maximum rainfall values within each station and also leads to a variation in the number of events selected in each station. The threshold is calculated using the equation:

$$Threshold = \frac{(x*(n_d+1))}{100} \quad (2)$$

where x is percentile (1, 2, ..., 99) and n_d is the number of elements in the dataset. Rainfall data must be ordered first from the smallest to the largest value and the value of precipitation < 1 mm is not included in the calculation of the threshold.

The threshold values were then obtained with the 95% percentile and 30% percentile methods. Rainfall exceeding (below) the 95th (30th) percentile threshold is then categorized as extreme (non-extreme) rainfall events. Extreme (non-extreme) rainfall events during 1988-2014 as the reference for collecting atmospheric parameters data to be used for the composites analysis to explain the role of atmospheric conditions on extreme (non-extreme) rainfall events.

Moisture Flux

Moisture flux is the horizontal transport of water vapour by the wind. It plays a very important role in the development of precipitation. The variability in atmospheric moisture flux plays a crucial role in the terrestrial hydrological response and their fluctuations can relate directly to extreme rainfall events. Moisture flux is calculated by the equation below:

$$\text{Moisture Flux} = q * u_h \qquad (3)$$

where q is the specific humidity (kg/kg) and u_h is the horizontal wind (ms^{-1}). Moisture flux is also often referred to as the horizontal transport or advection.

Chapter summary

In this chapter, a brief description of the methods has been given that will be used to achieve the aims of this study, with specifics given where appropriate (i.e. changes to the models or regions of specific interest). Throughout this chapter various types of data from reanalysis to observational and methods have been described for their respective use to achieve the aims and objectives of this study. Figure 7 gives an overview of the overall experiment design of this study.

CHAPTER FOUR

RESULTS AND DISCUSSION

Introduction

This chapter presents a general description of the atmospheric variables considered for analysis in this study. Also, a trend analysis of precipitation over the study period is addressed. Subsequent detailed analysis of rainfall characteristics is presented as a comparison of extreme and non-extreme events, which were identified using cut off thresholds. The last part deals with the use of reanalysis data to conduct a further investigation into individual flooding events in order to understand the atmospheric conditions prior, during and after the extreme rainfall event.

Correlation analysis

The ERA-Interim data has been validated with the ground based GMet data using the methodology discussed (Bharti,2015). The coefficient of determination was calculated between the daily rainfall derived by GMet and ERA- Interim reanalysis data sets using scatterplot over Ghana. The graph shows a positive coefficient of 0.23 (R^2) indicating a 23% of the trend in the observational dataset can be observed in the re-analysis dataset. The slope of regression was found to be positive and correlation was found to be significant even at 95 % (p ~ 0) significance level.

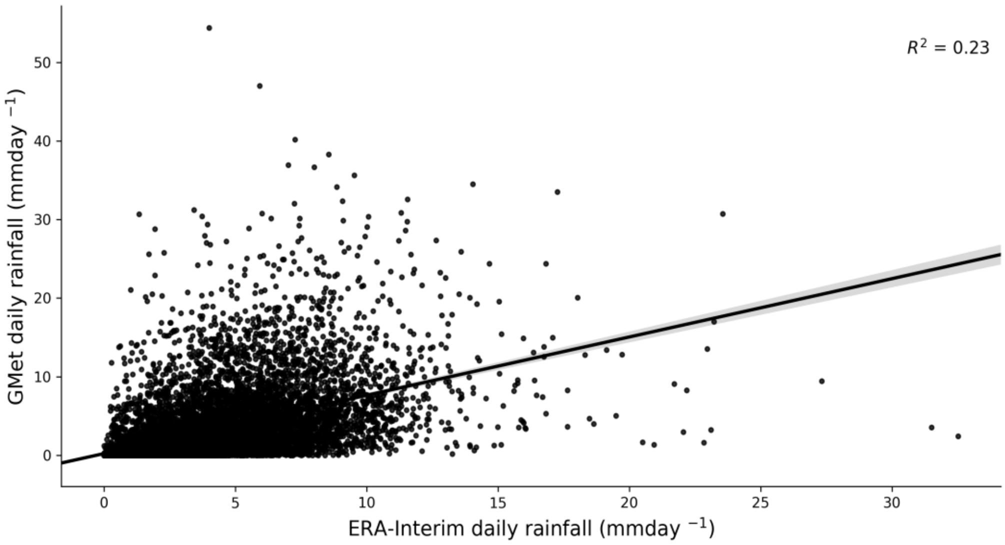

Figure 8: Correlation between GMet Average Daily Rainfall Data (represented on y-axis) and ERA-Interim reanalysis derived Average daily Rainfall (shown on x-axis) data over Ghana. The line shows the linear fitting of the data.

Annual cycle of precipitation

Figure 9 shows the monthly distribution of precipitation over Ghana. This figure shows a unimodal rainfall over the northern part of Ghana ranging from 9^{o} N to 11^{o} N in the months of May through to August. The southern part of the country experiences a bimodal rainfall regime as seen which is referred to as the major (March-July) and minor (September-November) rainfall seasons. The major wet season is observed to experience a peak in the month of June with the minor season peaking in October. August happens to have fewer rains as low as 3 mm on the average which is sandwich between the two wet seasons over Southern Ghana. The different rainy seasons account for the number for growing seasons in the country with the Northern part having just one growing season and the Southern part having two growing seasons for agriculture purposes.

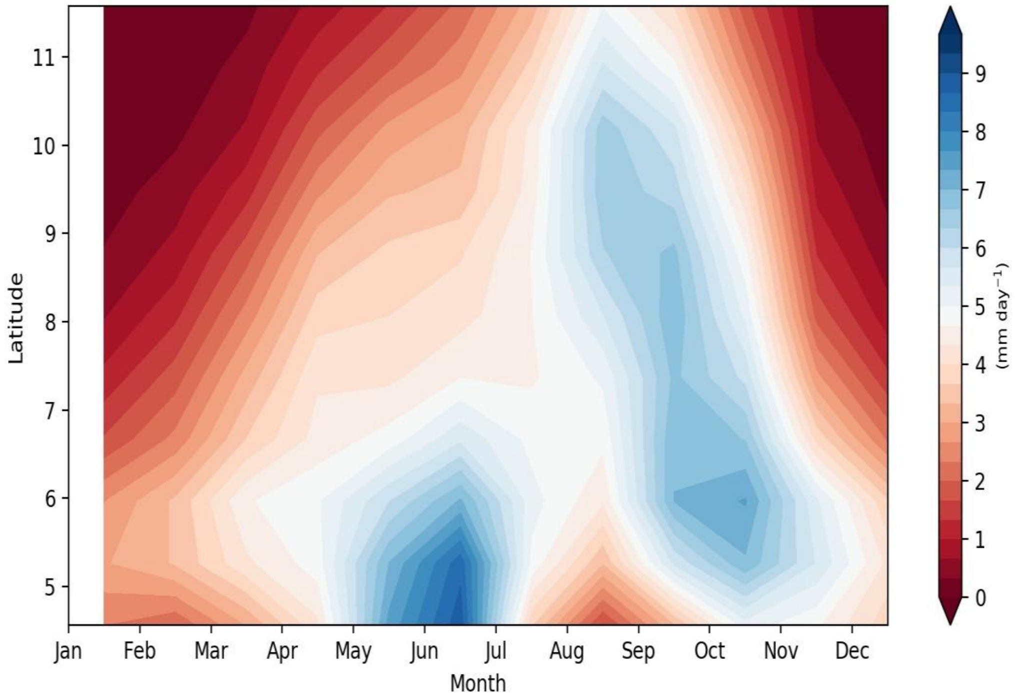

Figure 9: Time-latitude cross-sections of ERA-Interim long-term average Precipitation averaged across 4 ^{o}W and 2 ^{o}E.

Spatial distribution of seasonal precipitation

Seasonal variability of rainfall over Ghana is represented in Figure 10. The AMJ season which is a cumulative average of the precipitation intensities over the April-May-June which happens to be the start of the major rainfall period in the southern part of Ghana per this study. Rainfall values begin to increase from about 2 mm in the north to as high as 8 mm in the south, typically geared towards the southwestern corridor of the country with the rest of southern Ghana recording rainfall means ranging from 3 mm – 5 mm. The Northern part does record low intensities of rainfall < 3 mm during the AMJ season. This is shown in Figure 10(a) and this also accounted for by (Baidu, Amekudzi, Aryee, & Annor, 2017; Aryee, 2016). During this season the monsoon winds result in the movement of the ITD from its southern position towards the northward bringing with its moisture into the country. Figure 10(b) the SON season is known to be the minor rainy season for the southern part of Ghana. Rainfall amounts vary between 4 mm and 10 mm for the south and the boundary between the northern and the southern of Ghana. The upper part of the north thus experiences a relatively lower rainfall and the south-west of the country is observed to record more intense rainfall. This minor season is characterised by the swift return of the ITD southwards (Aryee, 2016; Baidu et al., 2017). DJF is the season with little rainfall throughout the country with a mean rainfall of 5 mm or less Figure 10(c). Within this season, air masses originating from the high-pressure system above the Sahara Desert give rise to dusty Harmattan winds causing the ITD to move southwards beyond the country. Spatial distribution of seasonal specific humidity in Figure 11 shows that the specific humidity decreases rapidly from the wet season to the dry season. The specific humidity over the season has reduced from AMJ through to SON and DJF.

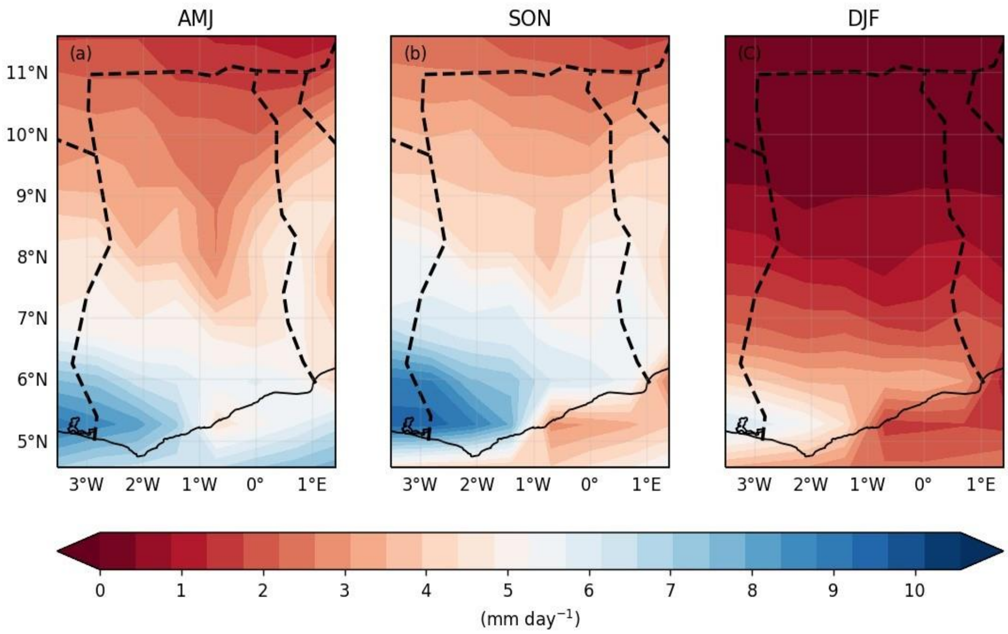

Figure 10: Daily Mean Rainfall (mm) over Ghana for (a) April to June, (AMJ) (b) September to November, (SON) and (c) December to February, (DJF) during the 1988–2014 period.

Spatial distribution of seasonal specific humidity

The seasonal mean surface specific humidity is represented in Figure 11. In this figure, it is seen that surface specific humidity is present during both wet seasons and dry season with varying magnitudes. High magnitude of specific humidity is present in AMJ season as compared to SON and DJF with DJF having the least amount of specific humidity throughout the season with the lowest over the north (~0.004 kg kg^{-1}). The amount of rainfall over these seasons can thus correlate well to the amount of specific humidity recorded as the saturation of humidity in the atmosphere can result in more rainfalls which is evident in the wet seasons. The amount of rainfall seen over the DJF can be as a result of the presence of specific humidity in the atmosphere.

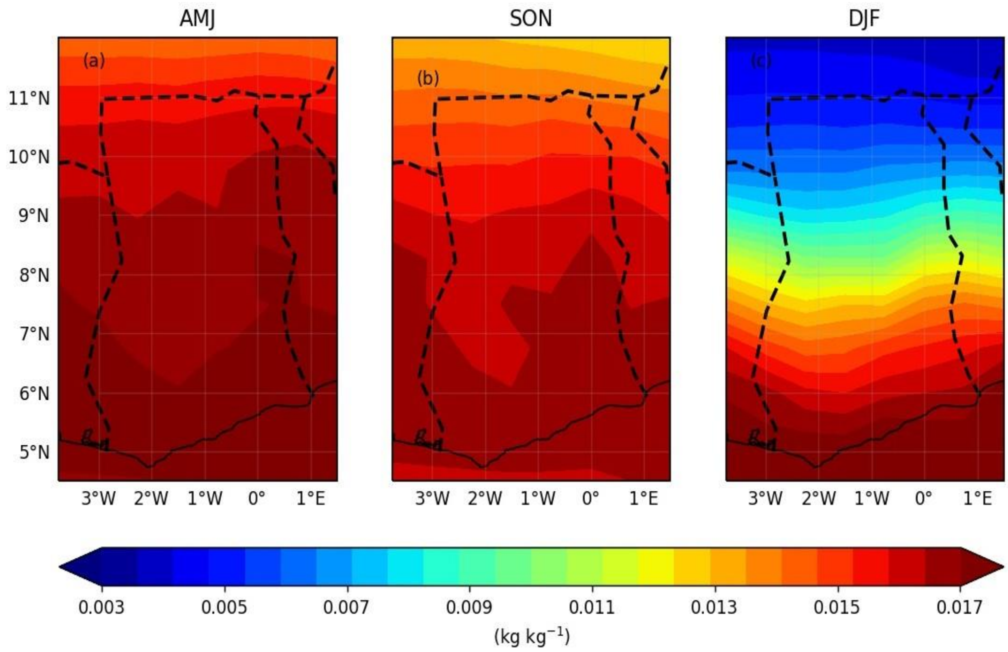

Figure 11: Climatological average of Surface Specific Humidity for (a) AMJ, (b) SON, and (c) DJF. Data are from the ERA-Interim reanalysis for a 27-year period from 1988 to 2014.

Spatial distribution of seasonal wind speed and direction

Figure 12 is a representation of the seasonal wind averages for 850 hPa, 700 hPa, and 200 hPa. The composite wind vectors directions during AMJ at 850 hPa is dominated by southeasterly winds whilst at 700 hPa northeasterly wind direction is observed. At 200 hPa for AMJ, a strong easterly wind direction is seen as compared to SON and DJF. During SON at 850 hPa and 700 hPa, the pronounced wind direction is northeasterly but at 200 hPa level, the vectors are seen to be southeasterly. DJF, which is a representation of the dry season in Ghana, is seen to be dominated by northeasterly at both 850 hPa and 700 hPa with varying wind speeds with 200 hPa exhibiting a southwesterly wind direction.

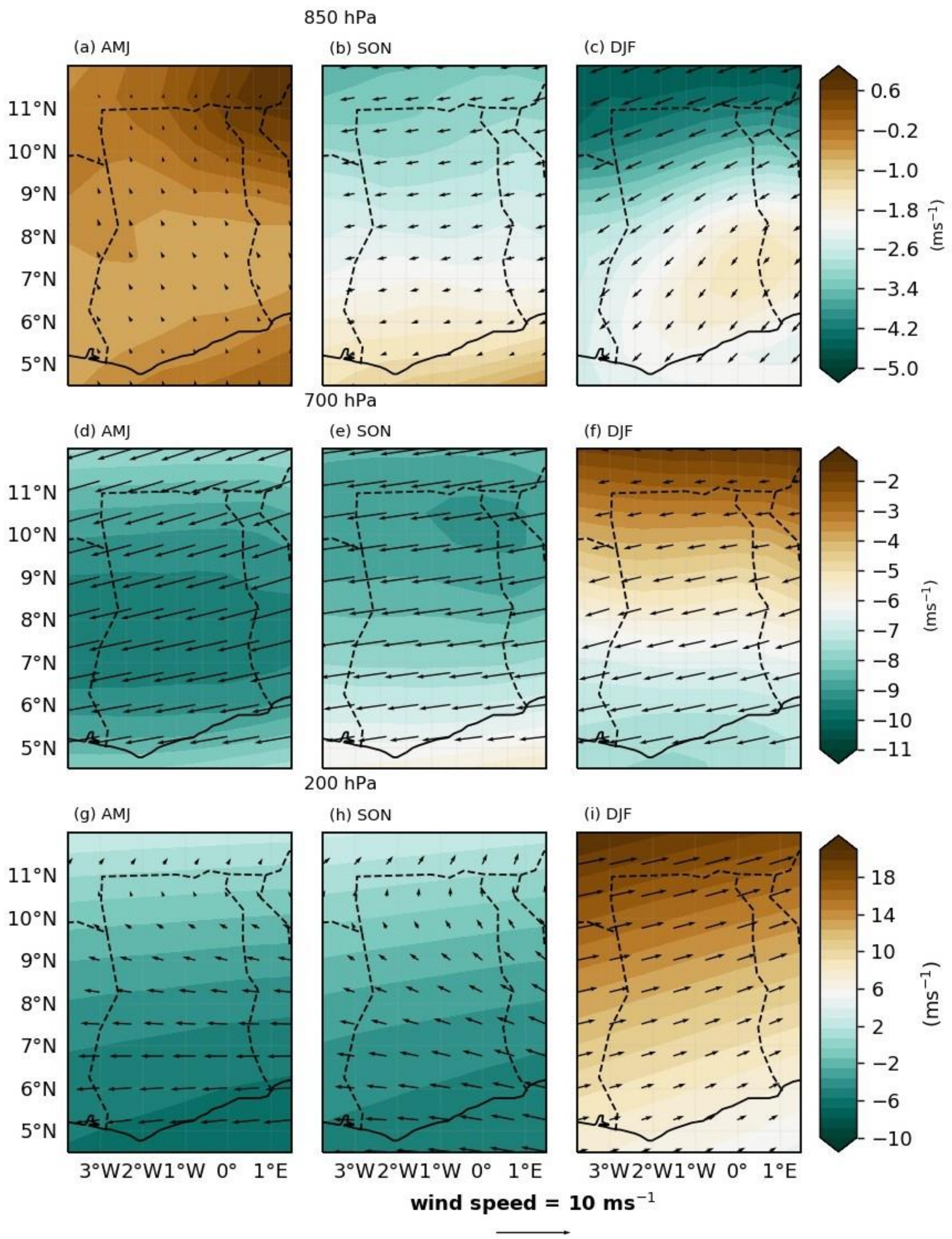

Figure 12: Climatological averages of wind for (a) 850 hPa, (b) 700 hPa, and (c) 200 hPa. Data are from the ERA-Interim reanalysis for a 27-year period from 1988 to 2014.

Spatial distribution of seasonal Moisture Flux

Figure 13 displays the absolute magnitude and direction of the moisture flux over Ghana on a seasonal basis, within the lower troposphere, using Equation (3). The dominating northward intrusion of the Atlantic Ocean moisture into the southern and northern areas contributes toward the precipitation in the wet season. This large-scale northward intrusion of the moisture flux into Ghana during the wet season may act as an enhancement factor for the disturbances giving rise to the individual precipitation events depending upon the spatial and the temporal details of the selected case study event (Mujumdar, 2006). Though there is small contribution of the moisture flux from the Atlantic Ocean in the dry season, however because of the Azores high pressure system located at about 30^{o} N and warmer temperatures over Ghana during this season, this moisture flux does not seem to play a dominant role in the precipitation. There is small precipitation in the southwest region of Ghana in the dry season, associated with the northward movement of the ITCZ over Ghana. As has been indicated in several of the recent studies, the precipitation occurrence is dominated during the wet season in Ghana (Baidu et al., 2017). During the dry season, the precipitation is confined to the southwestern region of Ghana.

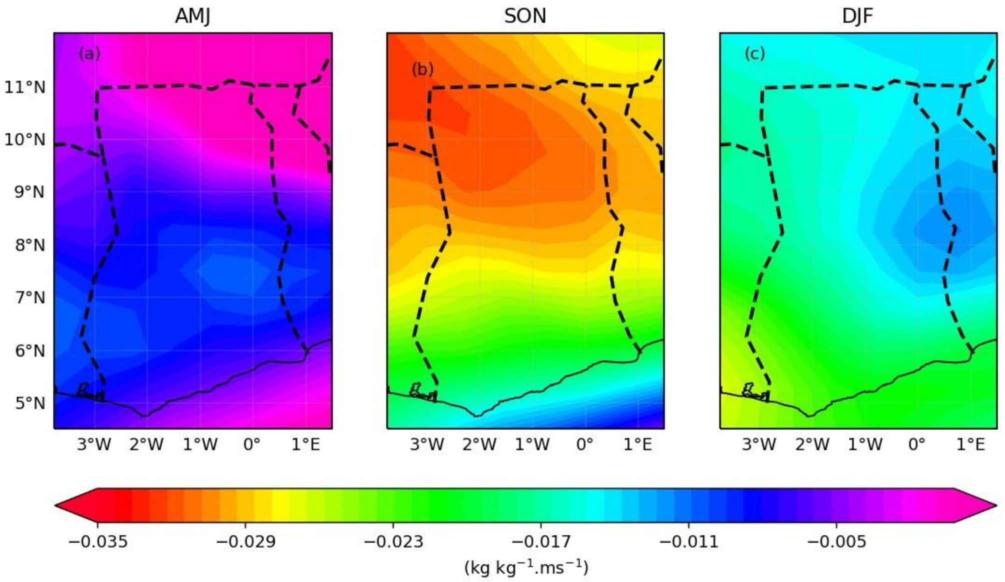

Figure 13: Climatological averages of Moisture Flux (ms^{-1}) at 850 hPa. Data are from the ERA-Interim reanalysis for a 27-year period from 1988 to 2014.

Trend analysis for Extreme rainfall

Figure 14 is a graphical representation of the mean total annual precipitation for Ghana over a duration of 27 years generated with ground-based data from GMet and a reanalysis data respectively. The annual precipitation totals over the entire country are observed to be increasing over the study period as shown in ground-based dataset with the re-analysis dataset indicating a decreasing trend. Although the observational dataset does not show a statistically significant trend, that of the reanalysis dataset does show a significant trend at 95% confidence level using the P-value test of significance.

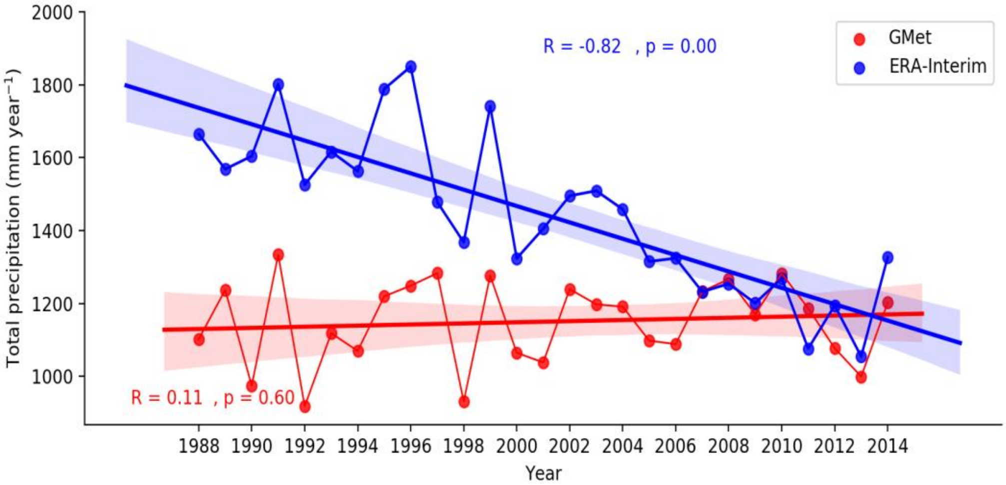

Figure 14: Annual Rainfall Totals in Ghana for the period 1988-2014 from (a) ground-based data (b) re-analysis data.

Rainfall above a 95th percentile threshold is analysed seasonally using daily dataset. The contribution of extreme rainfall to the annual rainfall total is seen to have decreased over the climatological period (1988 – 2014) as shown in both observational data and confirmed by the Re-analysis data for the AMJ season (Figure 15). Also, the minor rainfall season SON displayed in Figure 16 does show an increasing trend for the contribution of extreme rainfall to the annual rainfall amounts seen in the observational dataset. Although the reanalysis data from ERA-Interim shows a decreasing and significant trend for AMJ season the others show a non-significant decrease using the P-value test of significance with 95% confidence level and also high R showing there existence of a linear relationship. AMJ thus show the season with the highest extreme rainfall contribution over the years of study as compared to SON. Generally, there has been a decrease in the amounts of extreme rainfall contribution over the years of study as compared to SON. The disparity in the rainfall magnitude for the observational data and reanalysis data can be as a result in their resolution.

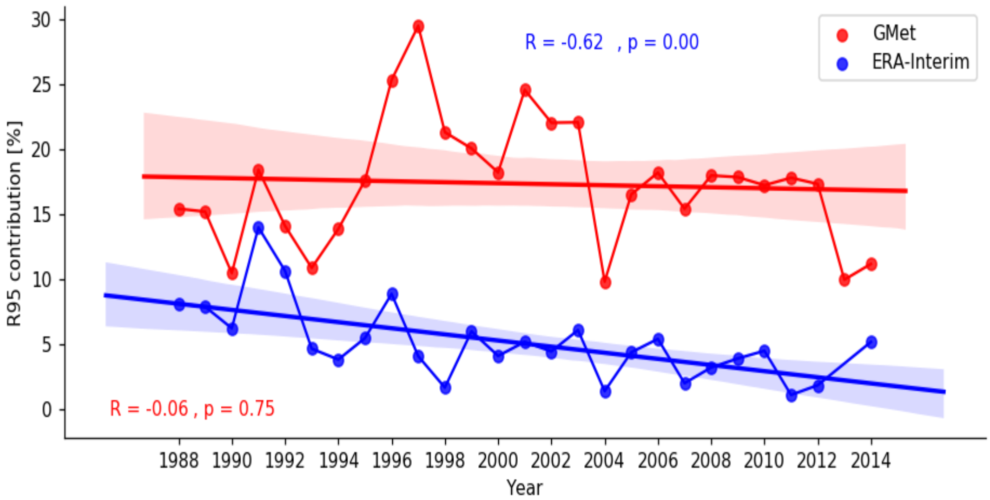

Figure 15: Percentage contribution of Extreme Rainfall to Annual Rainfall for the major rainfall season (April to May) for the duration 1988 - 2014 from (a) ground-based data (b) re-analysis data.

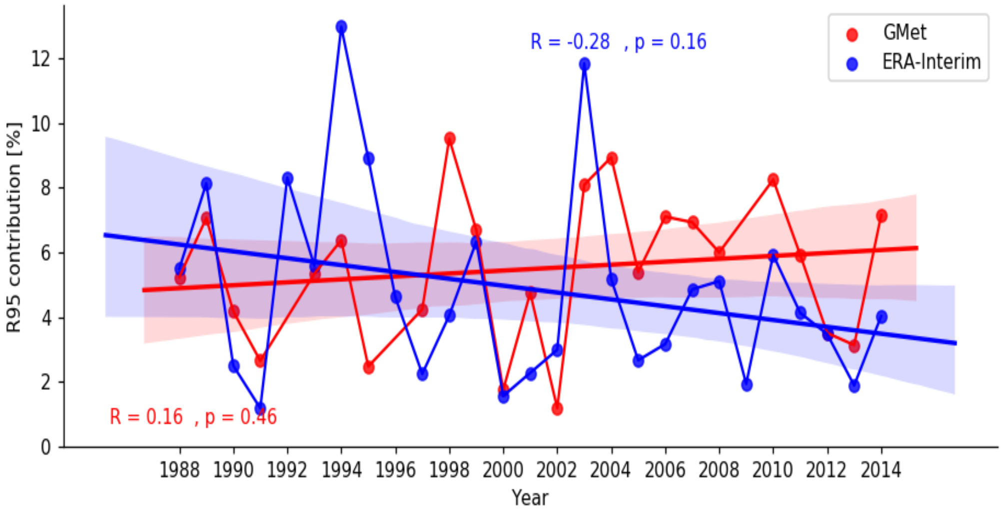

Figure 16: Percentage contribution of Extreme Rainfall to Annual Rainfall for SON for the duration 1988 - 2014 from (a) ground-based data (b) re-analysis data.

Atmospheric Conditions during Extreme and Non-Extreme Precipitation Events

For the first time, different daily precipitation threshold limits of 22 weather stations was constructed from a 27-year dataset (Figure 17). Two threshold limits were introduced; 30th percentile threshold (Figure 17a) and a 95th percentile threshold (Figure 17b) classified as non-extreme and extreme events respectively. Non-extreme events were selected as rainfall amounts that were below the computed 30th percentile threshold for each grid as extreme events were events above the 95th percentile threshold. According to the results, the highest daily precipitation rates exceeding 14 mm are observed in the southwestern corridor where it can be classified as "rich" in terms of extreme amounts of precipitation. Daily precipitation amount of a station located in the Southwestern exceeds this limit, that day is recorded as an extreme precipitation event for that station. A daily precipitation threshold ranging from 11 mm to 14 mm is shown to be mainly located on the forest zone. When one moves towards interior continental areas, the daily extreme precipitation threshold increases from 6 mm to 11 mm. The lowest limits are observed in the semi-arid continental areas of the savanna and transition zones, having threshold values lower than 10.5 mm, as illustrated in maroon in Figure 17. The threshold values over continental areas can be classified as "poor" in terms of extreme amounts of precipitation. During this day, daily precipitation means exceeding 8 mm are shown in blue as less than 7 mm are shown in maroon in Figure 17.

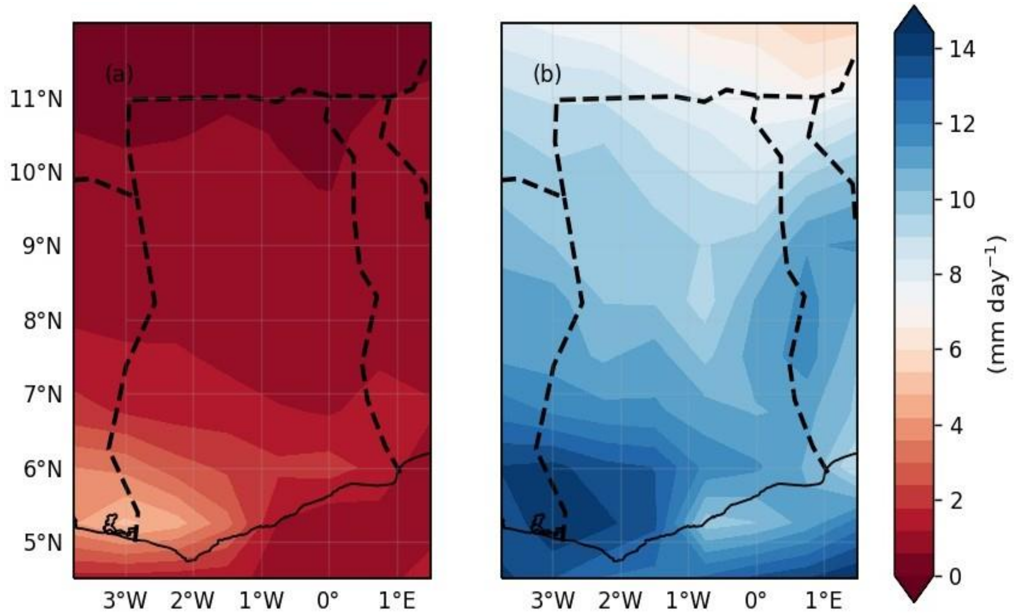

Figure 17: The map shows the threshold values (in mm) for the duration 1988–2014 (a) 30 th percentile, (b) 95 th percentile for generating an Extreme and Non-Extreme Precipitation Event.

The specific humidity distribution (Figure 18 (b)) is relatively higher in intensity during an extreme event than the non-extreme event over the study area. Similar observations were noticed for the associated precipitation (Figure 18 (a)), in the lower troposphere, based on the specific humidity behaviour. The lower panel in Figure 18 displays the lower tropospheric transport of the moisture flux during the extreme for the 27-year period (1988–2014). The lower panel displays the same for non-extreme events. The units for both panels are meter per second. In the extreme events, there is tongue of eastward moisture flux transport, throughout the lower troposphere. A westward transport is noticeable in the non-extreme events. Thus, relatively less moisture flux is transported westward from the Atlantic Ocean into the land area during non-extreme events as compared to during extreme events. Figure 19 displays the horizontal wind vector distributions for the three mandatory levels over the study area. In the case of extreme events, the wind circulation patterns are southwesterly throughout the troposphere at 850 hPa. Also, the wind circulation from the Atlantic Ocean to Ghana is more pronounced. On the other hand, during non-extreme events, the horizontal wind vector distribution is northeasterly reflecting the dominant presence of the Azores high-pressure system and the ITCZ over Ghana. At 700 hPa the dominant wind circulation direction is northeasterly for both Extreme and non-extreme events. Increase in the magnitude of winds occurs with extreme conditions, as compared to that in the non-extreme events is less. According to (Hellström, 2005; Vliet, 2016) precipitation amount can correlates well with wind speeds as stronger wind speeds correspond to higher precipitation. A noticeable reversal in direction of the wind vectors at 200 hPa during extreme event which shows a strong easterly wind with non-extreme is dominated by south easterly winds over the southern part of the country and southwesterly over northern Ghana.

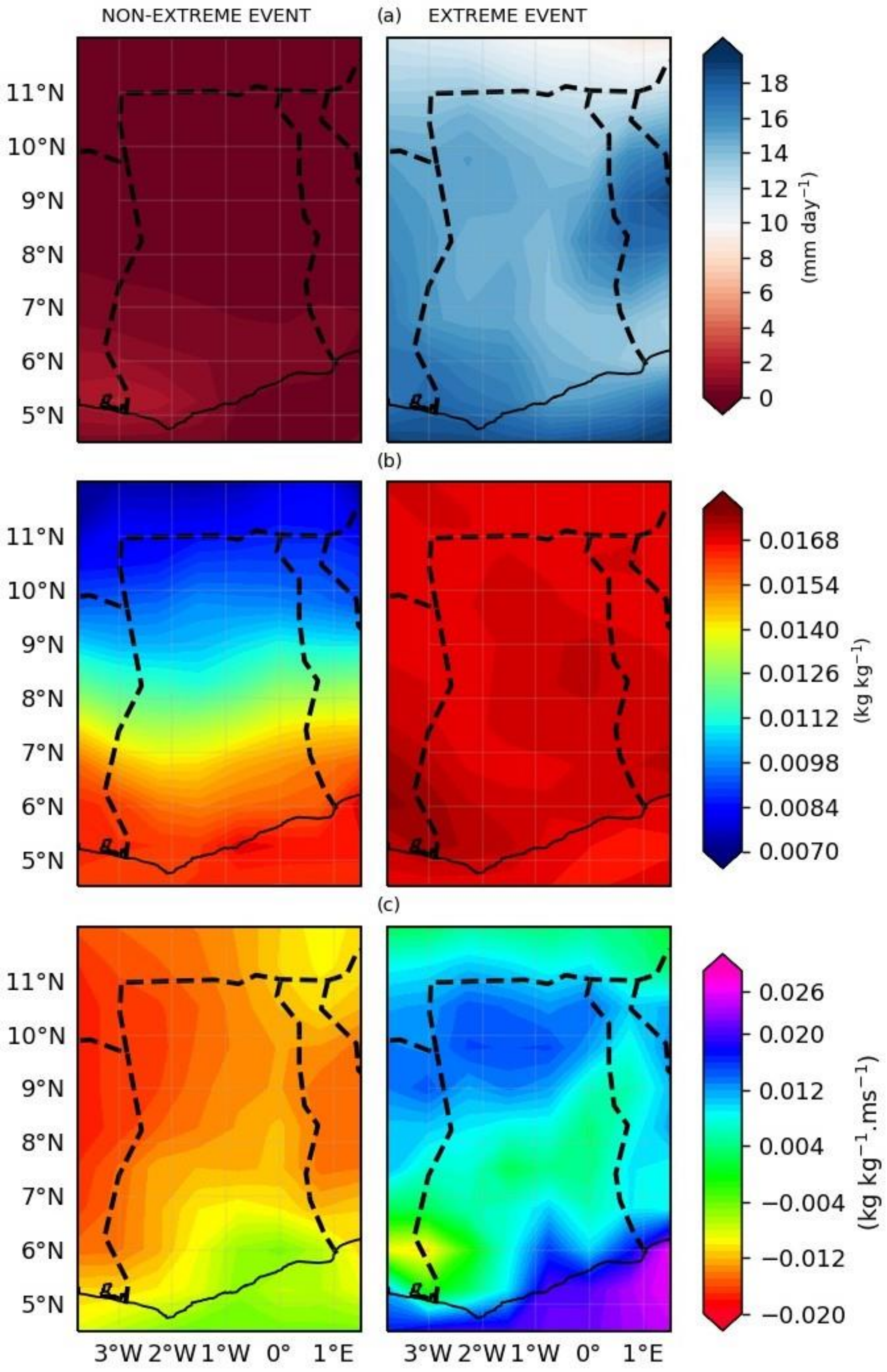

Figure 18: Composites for (a) Precipitation, (b) Surface Specific Humidity, (c) Moisture Flux for Non-Extreme Events (left column) and Extreme Events (right column).

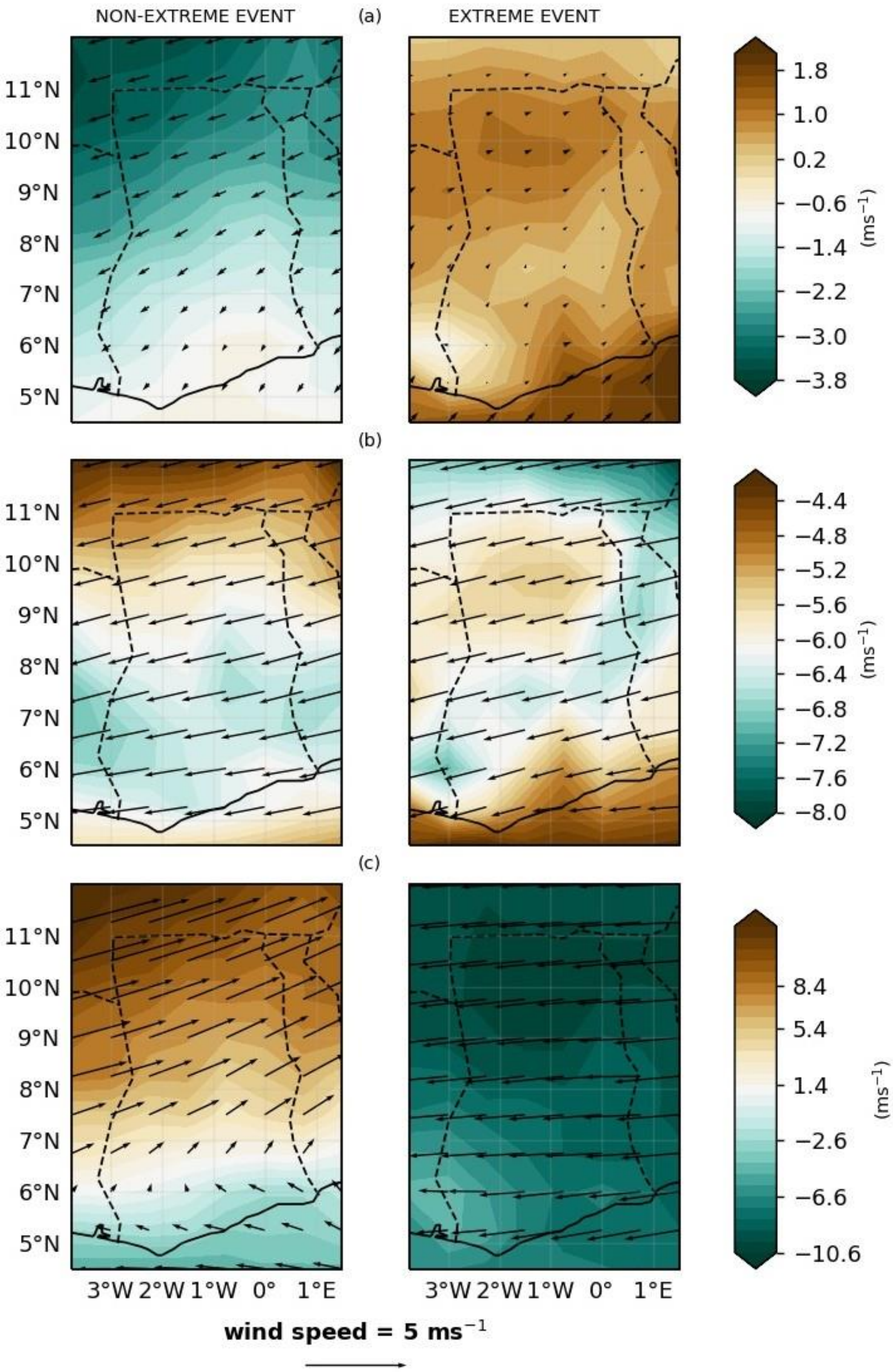

Figure 19: Composites of Horizontal Wind Velocity (ms −1) at (a) 850 hPa, (b) 700 hPa, and (c) 200 hPa for Non-Extreme Events (left column)and Extreme Events (right column).

Case Studies of Atmospheric Conditions Prior to Flood Events

In the case of flood events, Atmospheric conditions leading to the flood event can be examined before, during and after the event over Ghana. The specific humidity, horizontal (zonal) moisture flux and wind circulations can be estimated in order to find the relationships between the large-scale atmospheric conditions and the event under consideration. According to (Hall & Peyrillé, 2006) and (Akinsanola & Aroninuola, 2016) much of the variability in precipitation across West Africa can be explained by considering circulation at three different pressure levels; 850 hPa, 700 hPa and 200 hPa. Before evaluating the atmospheric conditions that lead to the extreme event there is a need to examine the spatial pattern of rainfall over Ghana before, during and after the event. Two flood situations were considered for further investigation. Both flood events occurred in the Greater Accra region as stated by (Asumadu-Sarkodie et al., 2015; Sanquah, 2013) and (Tengan, 2016). This synoptic event was characterised by heavy rains falling over the Greater Accra region leading loss of lives and property.

Case I: 04/07/1995 – Greater Accra – flood event

Figure 20 shows the precipitation distribution over Ghana but the discussion will be based on the Greater Accra region. It is observed that on the 2nd - 5th July there was appreciable amount of rainfall and this could have contributed to the flood event of the 4th July by the saturation of the soil which could no longer permit the penetration of rains after 3rd July leading to the running over of the rains on the 4th July leading to the flood event. Greater Accra recorded low rainfall amounts during the pre event days (2nd – 3rd, July). The state of the atmosphere suddenly changed nationwide when significant rainfall amounts were recorded on the 4th July and went relatively stable again on the 5th of July. The possible causes of this abrupt change in atmospheric conditions on the 4th of July is evaluated in the sections below.

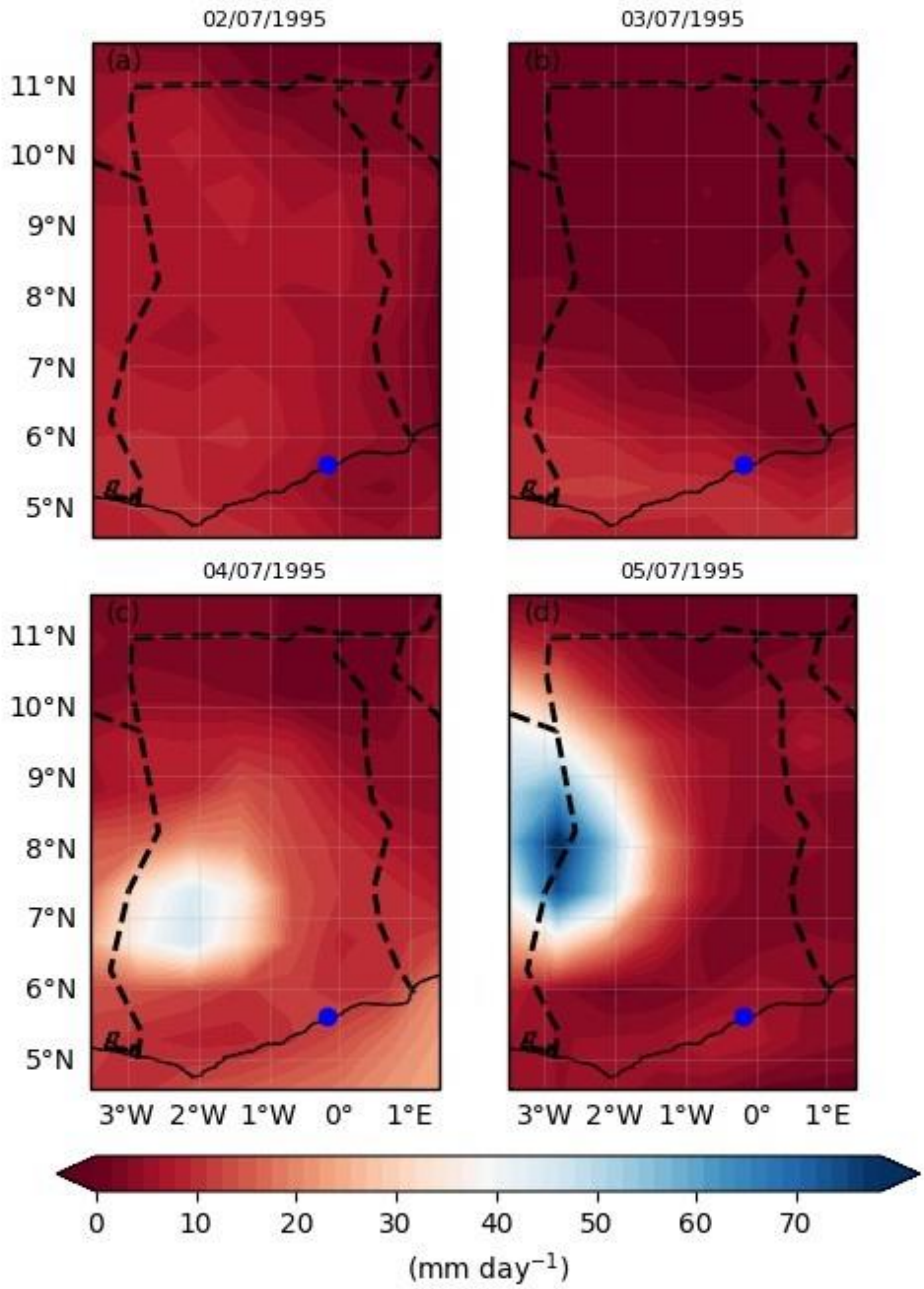

Figure 20: Precipitation for entire atmosphere for the Pre event days (a) 2nd July, 1995, (b) 3rd July, 1995, during the event (c) 4th July, 1995 and Post event day (d) 5th July, 1995.

From Figure 21, the specific humidity estimated for the period is presented. Corresponding to the rainfall amounts estimated in, high specific humidity is seen on the 4th of July (the event day). The western part of the transition zone where significant rainfall amounts was recorded also shows high specific humidity. Relatively less specific humidity was seen on the pre – event days, the amounts however increasing significantly on the 3rd of June (especially for the coastal zone). Interestingly, the specific humidity estimated nationwide reduced significantly on the post event day.

In order to access the amount of moisture that entered the country to bring about the rainfall, the zonal moisture flux was plotted in Figure 22. Zonal moisture flux increased gradually from the 2nd of July and reached its peak on the 4th of July but decreased significantly after the event. The moisture influx was particularly strong in the transition and the western parts of the savannah zone. The stronger moisture flux seen in this region may partly explain the high rainfall amounts that resulted (Figure 20(c)).

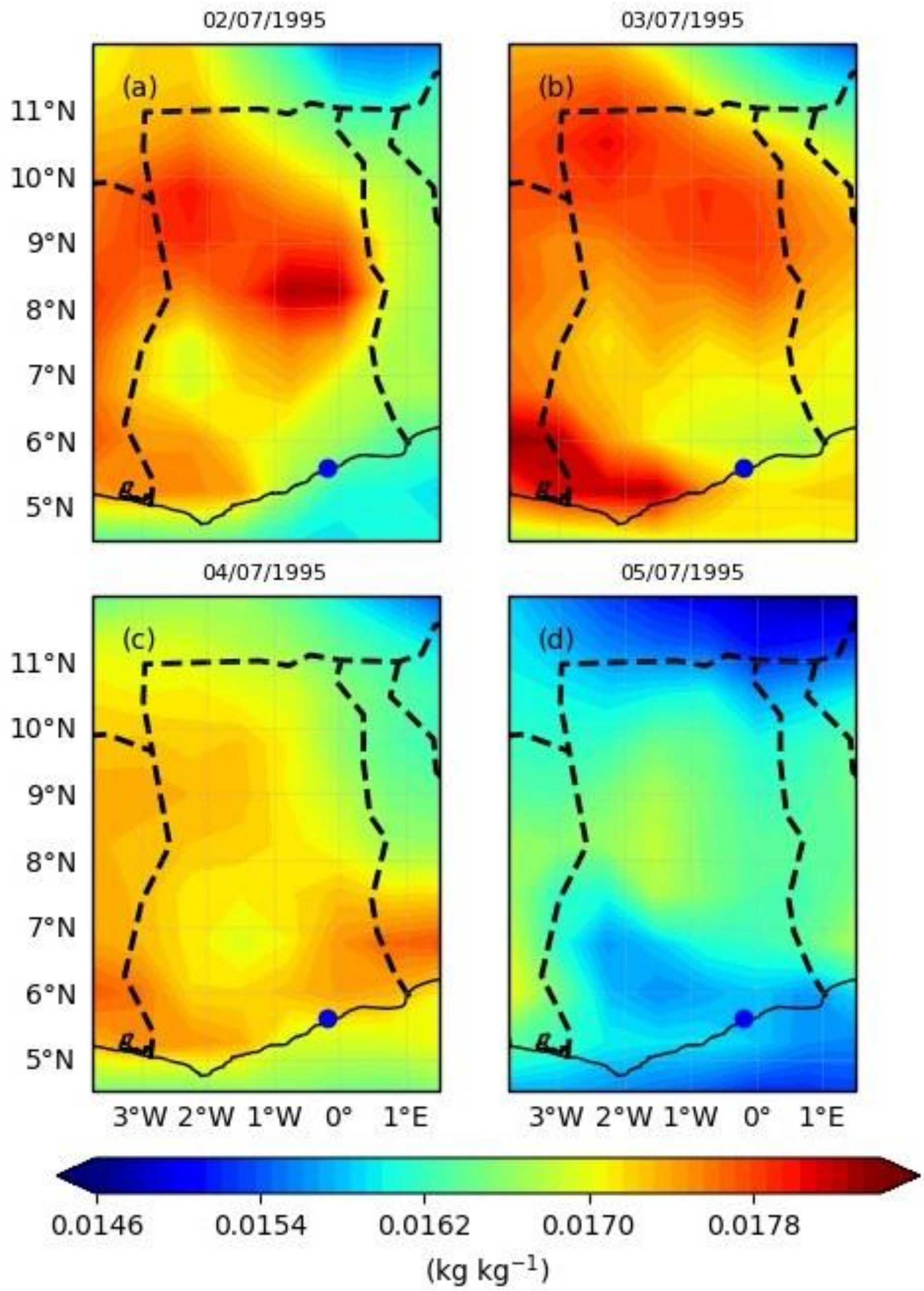

Figure 21: Specific Humidity for entire atmosphere at surface for the Pre event days (a) 2nd July, 1995, (b) 3 rd July, 1995, During the event (c) 4th July, 1995 and Post event day (d) 5th July, 1995

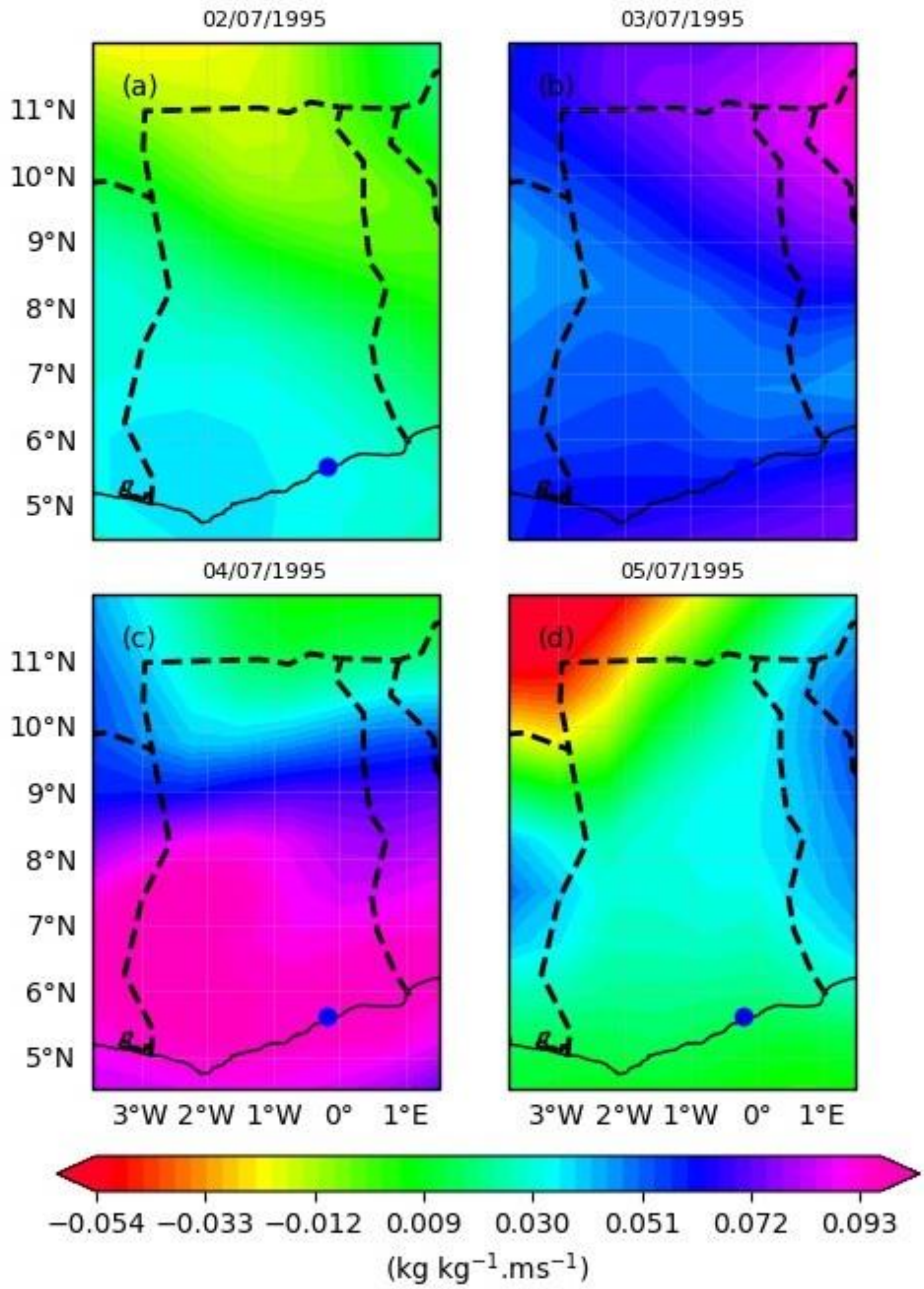

Figure 22: Zonal Moisture Flux for entire atmosphere at 850 hPa for Pre event days (a) 2nd July, 1995, (b) 3rd July, 1995, During the event (c) 4th July, 1995 and Post event day (d) 5th July, 1995.

The atmospheric circulation patterns observed before, during and after the event are also analysed using the horizontal wind velocities at 850 hPa, 700 hPa and 200 hPa. At the 700 hPa (Figure 24) the presence of easterlies is seen, indicating the presence of the AEJ. Strong winds on the 850 hPa level seen around the transition zone signifies the influx of low-level moisture required for the vertically development of convective storms (Figure 23(c)). This partly explains the high rainfall amount that was recorded in this region on the event day. Still on the event day, relatively stronger winds are observed along the coast at 850 hPa and the presence of westerlies seen at 700 hPa too. Stronger winds observed along the coast on the 850 hPa level on the 2nd and 3rd of July explains the high rainfall amounts recorded in the region during the period. The consistency of the easterly winds at 700 hPa during the period before the event favours the advection of convective storms, which are mostly initiated from Eastern Africa (Lin, 2009).

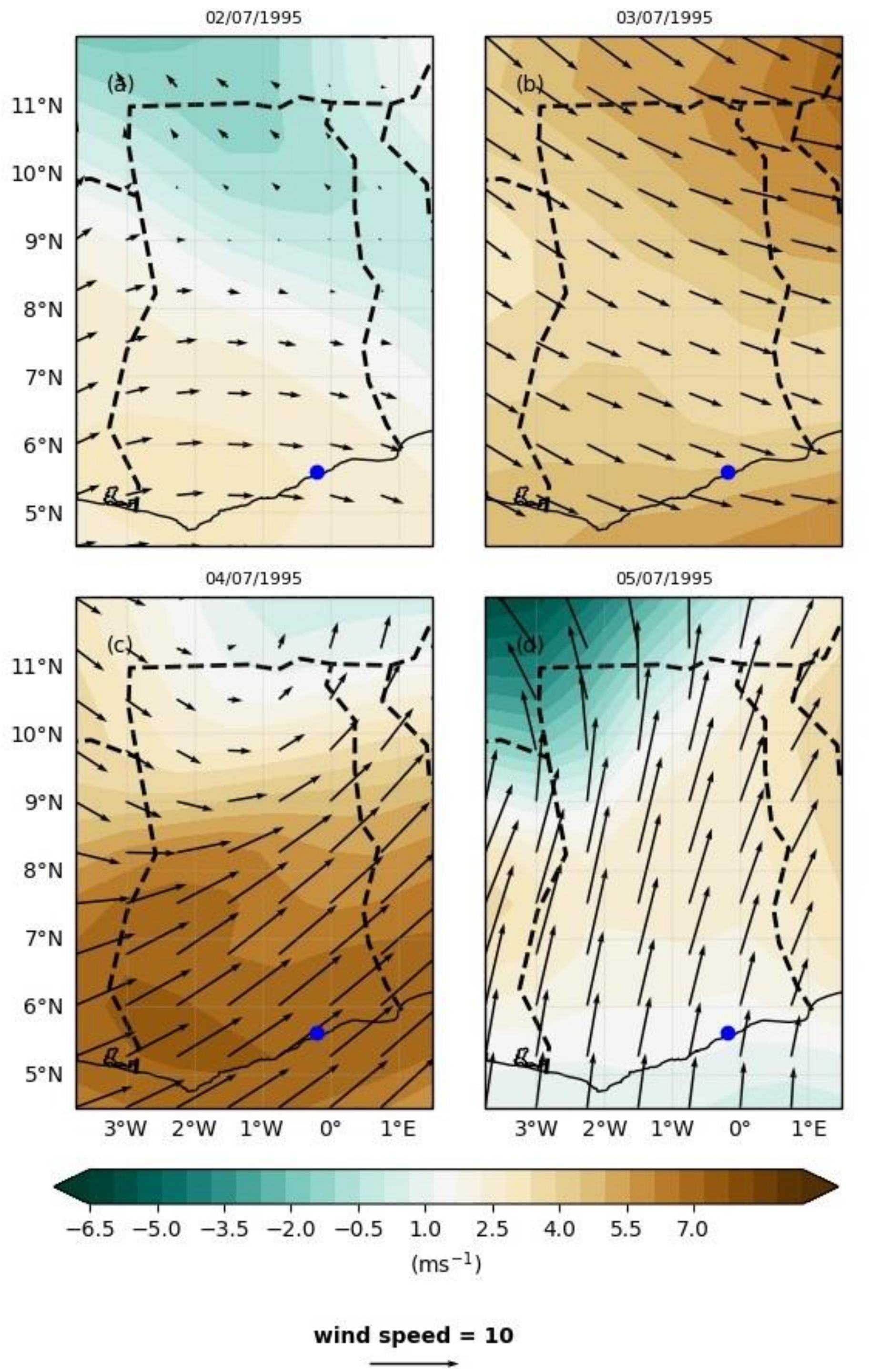

Figure 23: Horizontal Wind Velocity (shading) and an overlay for winds (vector) for entire atmosphere at 850 hPa for the Pre event days (a) 2nd July, 1995, (b) 3rd July, 1995, During the event (c) 4th July, 1995 and Post event day (d) 5th July, 1995

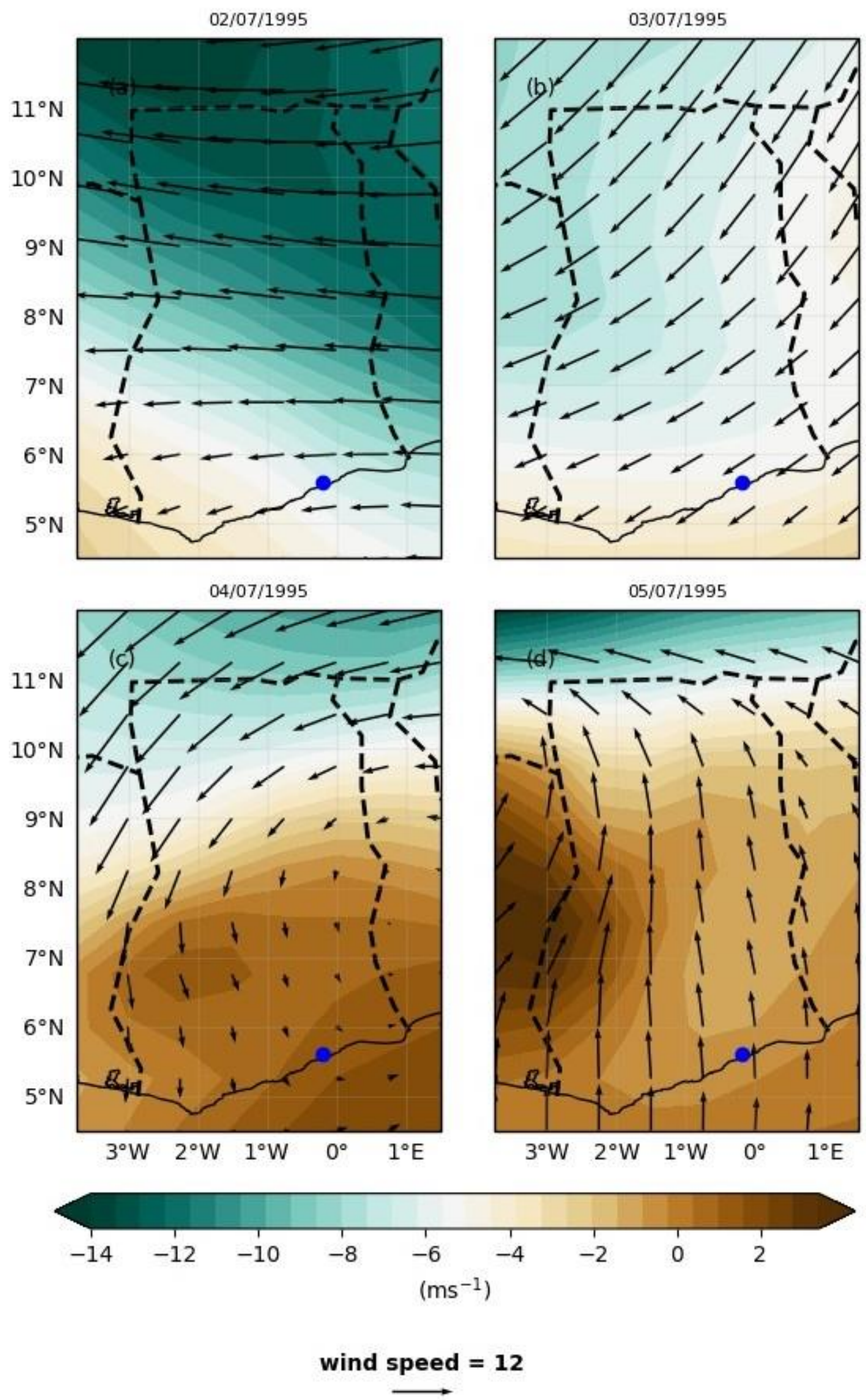

Figure 24: Horizontal Wind Velocity (shading) and an overlay for winds (vector) for entire atmosphere at 700 hPa for the Pre event days (a) 2nd July, 1995, (b) 3rd July, 1995, During the event (c) 4th July, ` 1995 and Post event day (d) 5th July, 1995

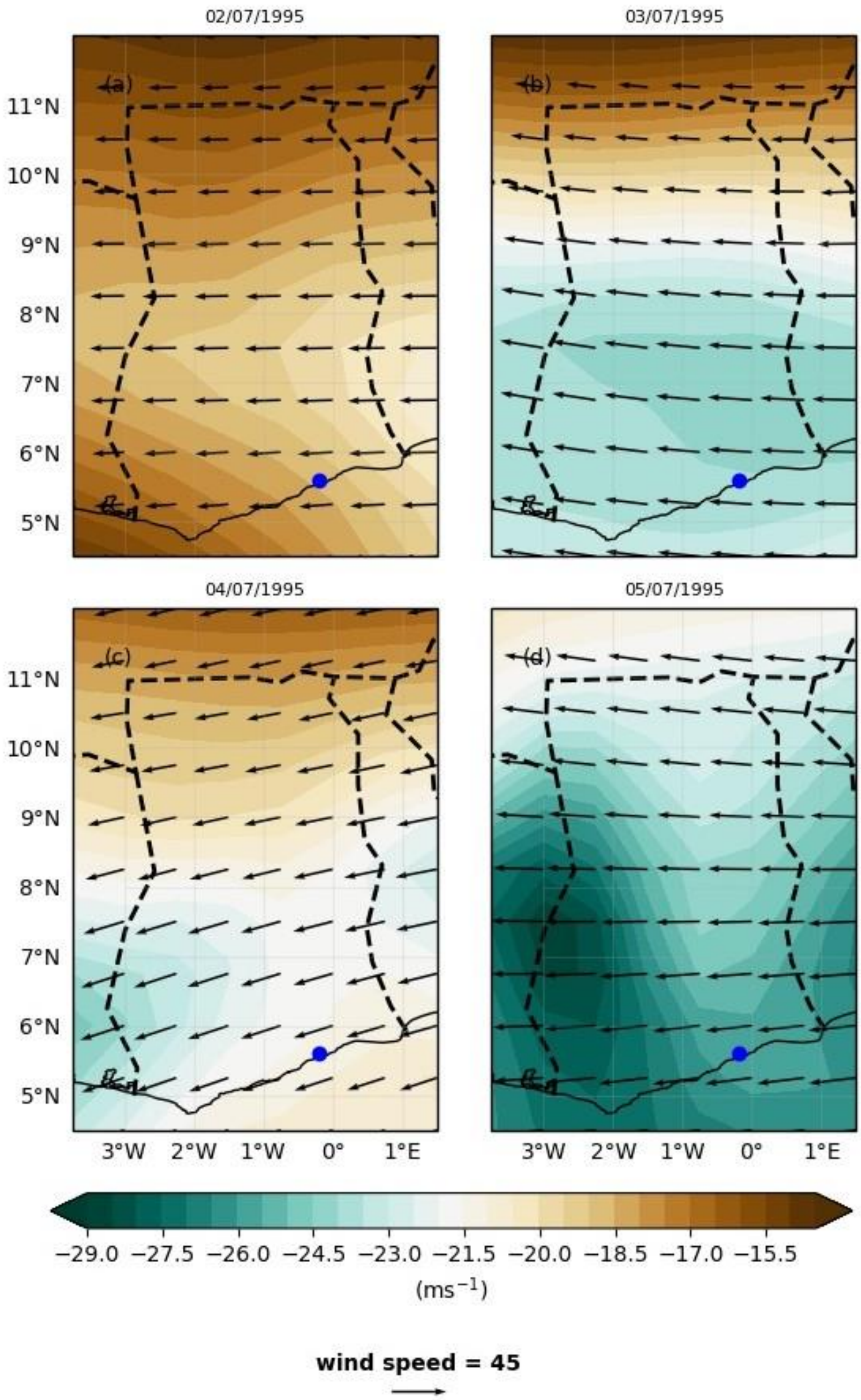

Figure 25: Horizontal Wind Velocity (shading) and an overlay for winds (vector) for entire atmosphere at 200 hPa for the Pre event days (a) 2nd July, 1995, (b) 3rd July, 1995, During the event (c) 4th July, 1995 and Post event day (d) 5 th July, 1995

Case II: 28/06/2001 – Greater Accra – flood event

From Figure 26, the total precipitation estimated during the pre event (26^{th} – 27^{th} June), the event (28^{th} June) and the post event (29^{th} June) are presented. Apart from the coastal and southwestern regions, low rainfall amounts (less than ~ 5 mm) were recorded over the country on the 26^{th} of June. The rainfall amounts increased slightly nationwide on the 27^{th} and very significantly on the event day (28^{th} June) with low amounts along the coastal zone. The nationwide rainfall amount however reduced significantly on the 29^{th} of June.

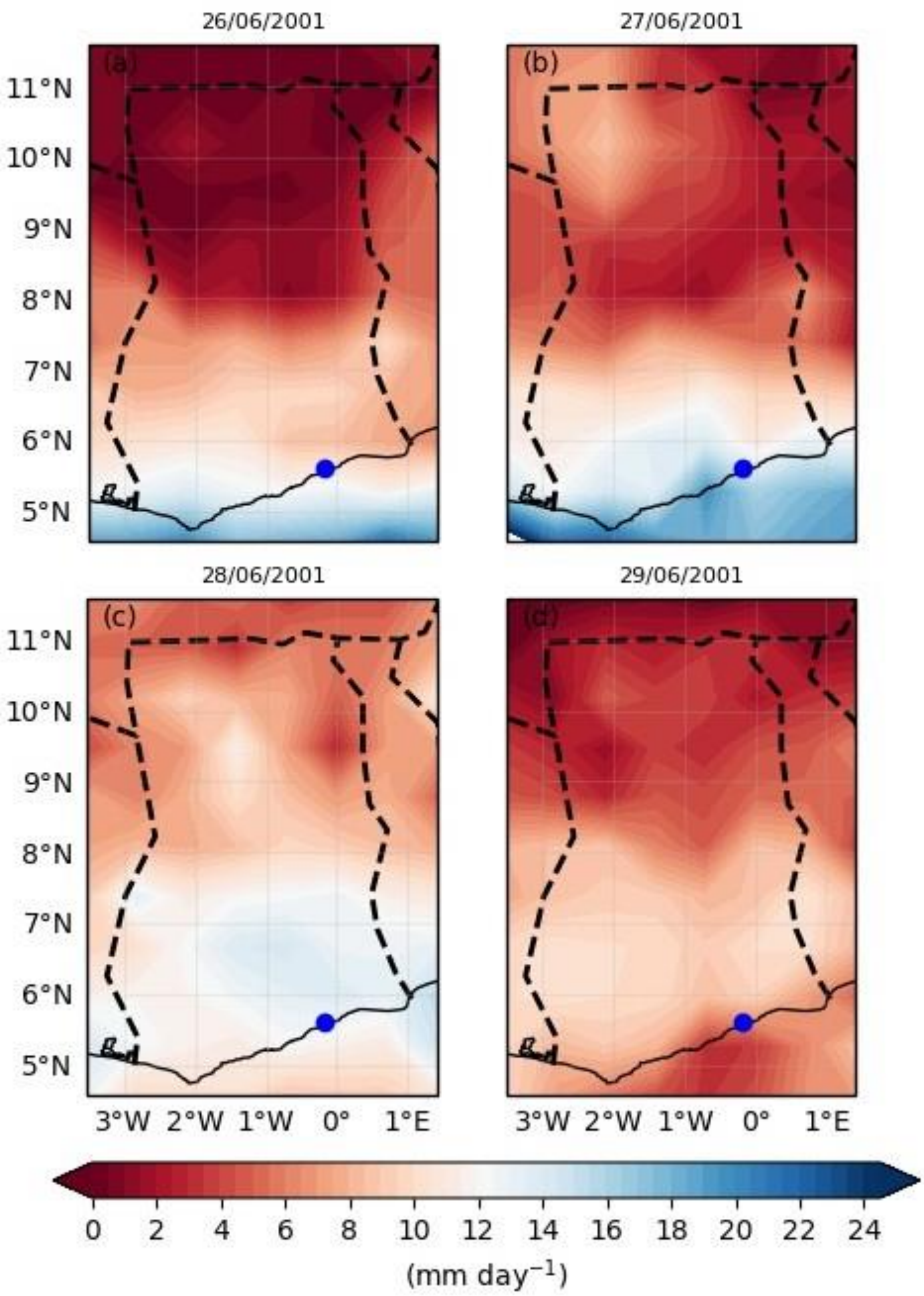

Figure 26: Precipitation (mm/day) for entire atmosphere for the Pre event (a) 26th June, 2001, (b) 27th June, 2001 During the event (c) 28th June, 2001 and Post event day (d) 29th June, 2001.

Figure 27 displays the specific humidity, distribution for the pre event, event day and post event day of the extreme rainfall occurrence. The specific humidity distribution is observed to be relatively higher during the pre event days around Greater Accra region, where the flood event largely took place (see Figure 26). The specific humidity seems to have subsided on the event day along the Greater Accra region. The post event day recorded low specific humidity across the entire country. Also, the amount of rainfall (see Figure 26) corresponds to the amount of moisture content in the air (Figure 28).

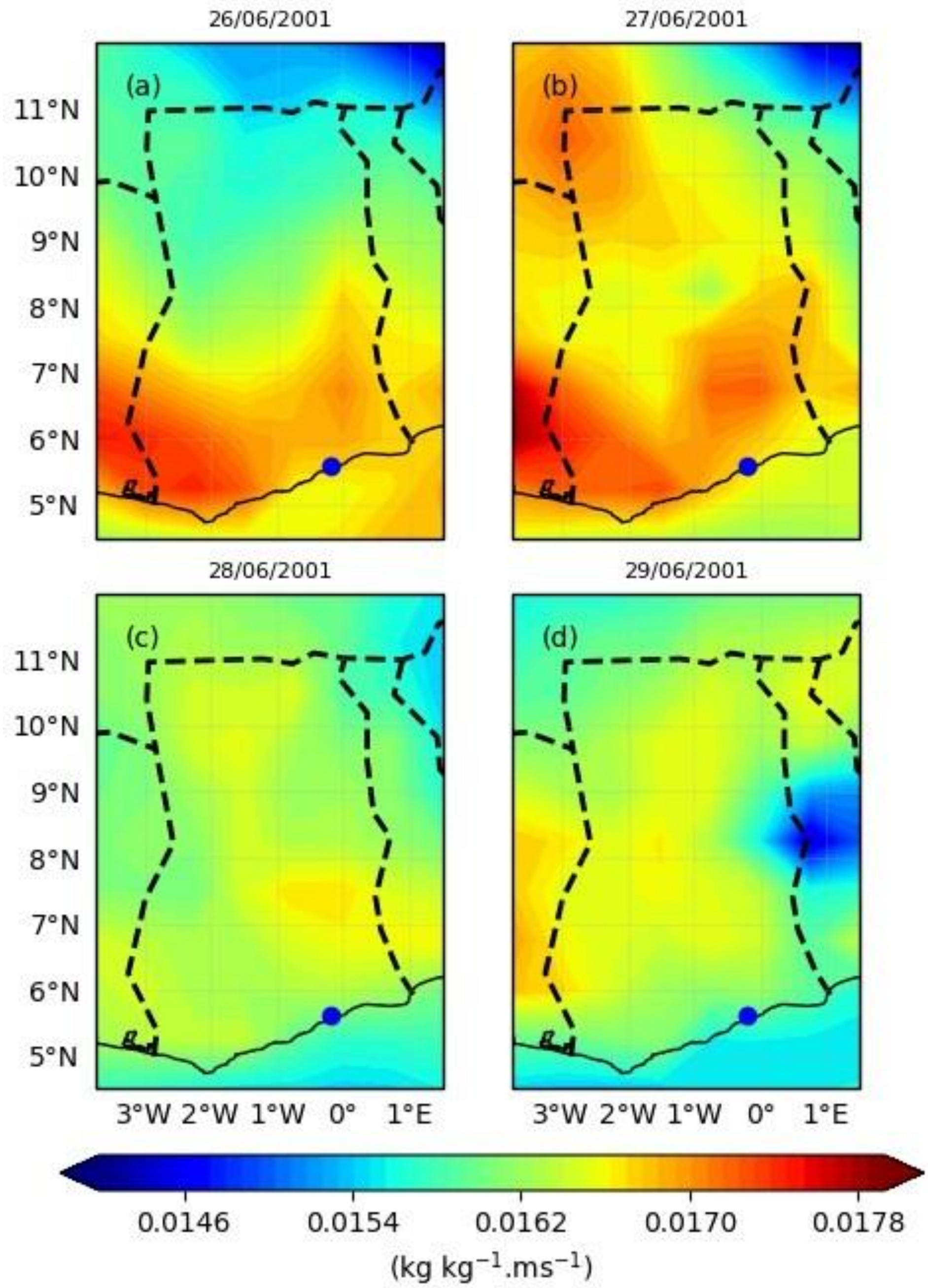

Figure 27: Specific Humidity for entire atmosphere at surface for the Pre event days (a) 26th June, 2001, (b) 27th June, 2001 During the event (c) 28th June, 2001 and Post event day (d) 29th June, 2001.

The zonal moisture flux (Figure 28) reveals a westward advection (positive values) across the region. This amount (ranging from 0 – 0.066 ms^{-1}) was relatively less than its equivalence (0 – 0.093 ms^{-1}) recorded in the previous case. This indicates that the rainfall event in this specific case has less influence from eastward advection as compared to the previous case.

Figures 29, 30, 31 display the zonal wind distributions at 850 hPa, 700 hPa and 200 hPa respectively. At 850 hPa, a progressively northwesterlies wind circulation is attained during 26th June and during 27th June the directions of the wind turned to be southwesterly which could have carried enough moisture into Accra resulting in the flood event. On the day of the event (28th June) the wind maintained the southwesterly motion but this time with a more intense wind speed as observed in the day before. This also may have increased the amount of moisture transported from the Atlantic Ocean inland. Also, a higher magnitude in zonal wind was also present on the day of the flood in the southern part of the country as compared to the pre and post event days. As seen in Figure 29, after the flood event, although the wind direction was still southwesterly, its speed was reduced.

At the upper level, (700 hPa), winds increase in speed and travel more westward than at 850 hPa on the 26th and 27th June (Figure 30). During the pre-event days, weak zonal wind was observed leading to a stronger zonal wind on the event day. Magnitude of winds tends to be low on the event day as compared to pre event and post event days.

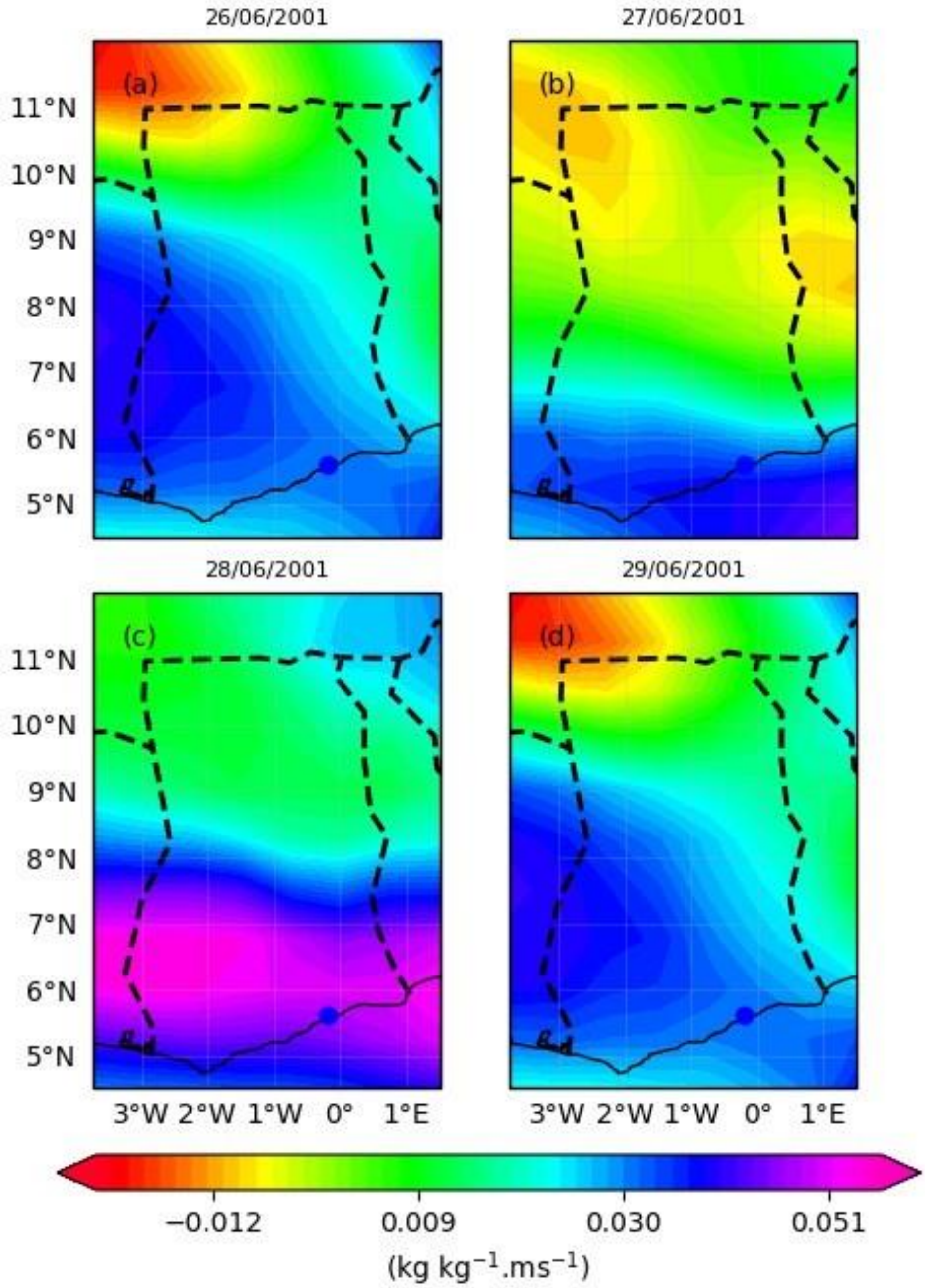

Figure 28: Zonal Moisture Flux for entire atmosphere at 850 hPa for Pre event days (a) 26th June, 2001, (b) 27th June, 2001 During the event (c) 28th June, 2001 and Post event day (d) 29th June, 2001.

At 200 hPa, wind circulation over Ghana was more pronounced (Figure 31). Stronger and more westward propagation of winds were observed at the 200 hPa level. On 27th June, the wind realizes a sharp decrease in intensity. The winds at this level regains strength on the post event day. The presence of a stronger zonal wind was observed during 28th June as compared to both pre, and post event days, with pronounce wind direction of north easterlies.

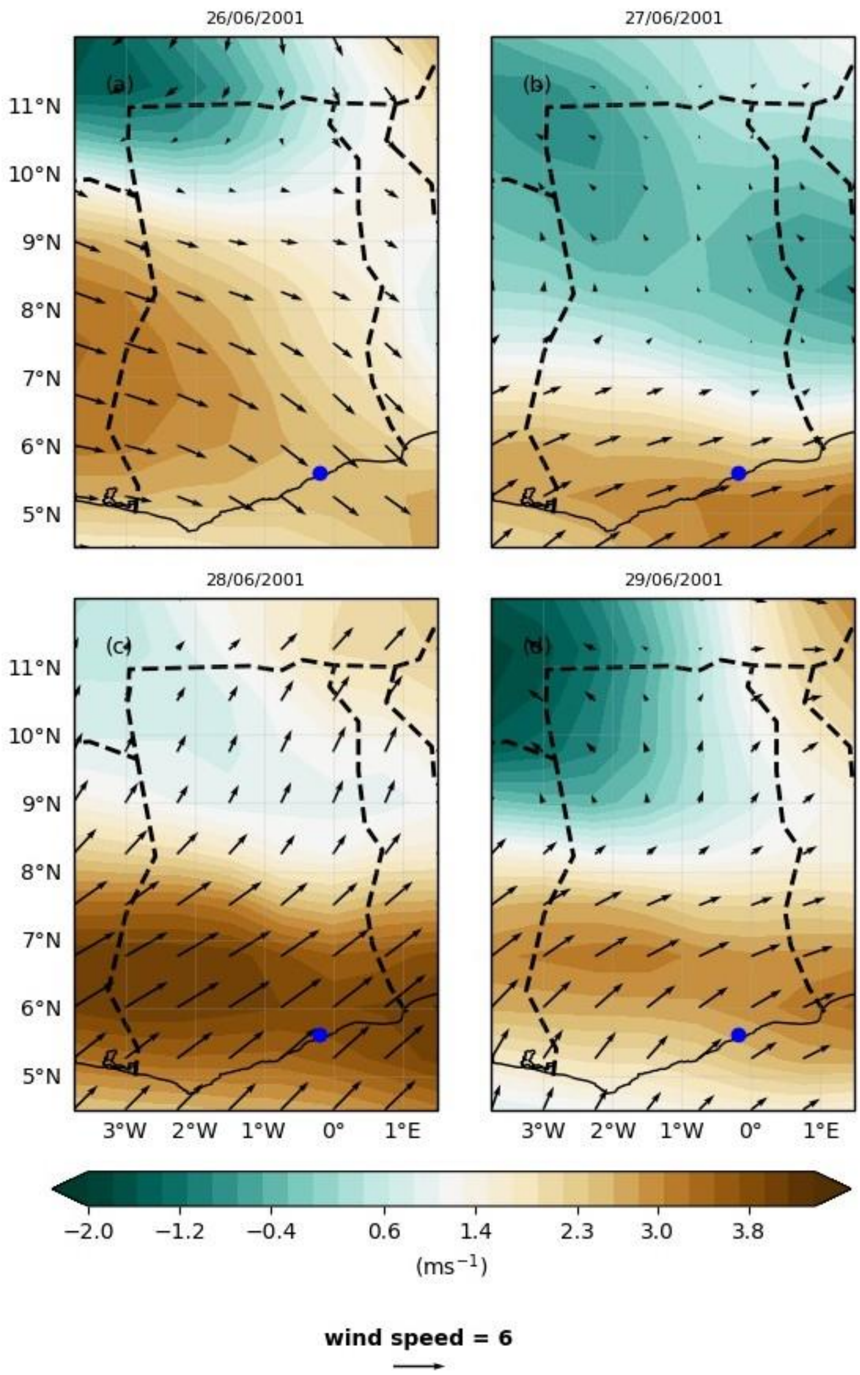

Figure 29: Horizontal Wind Velocity (shading) and an overlay for winds (vector) for entire atmosphere at 850 hPa for the Pre event days (a) 26th June, 2001, (b) 27th June, 2001 During the event (c) 28th June, 2001 and Post event day (d) 29th June, 2001.

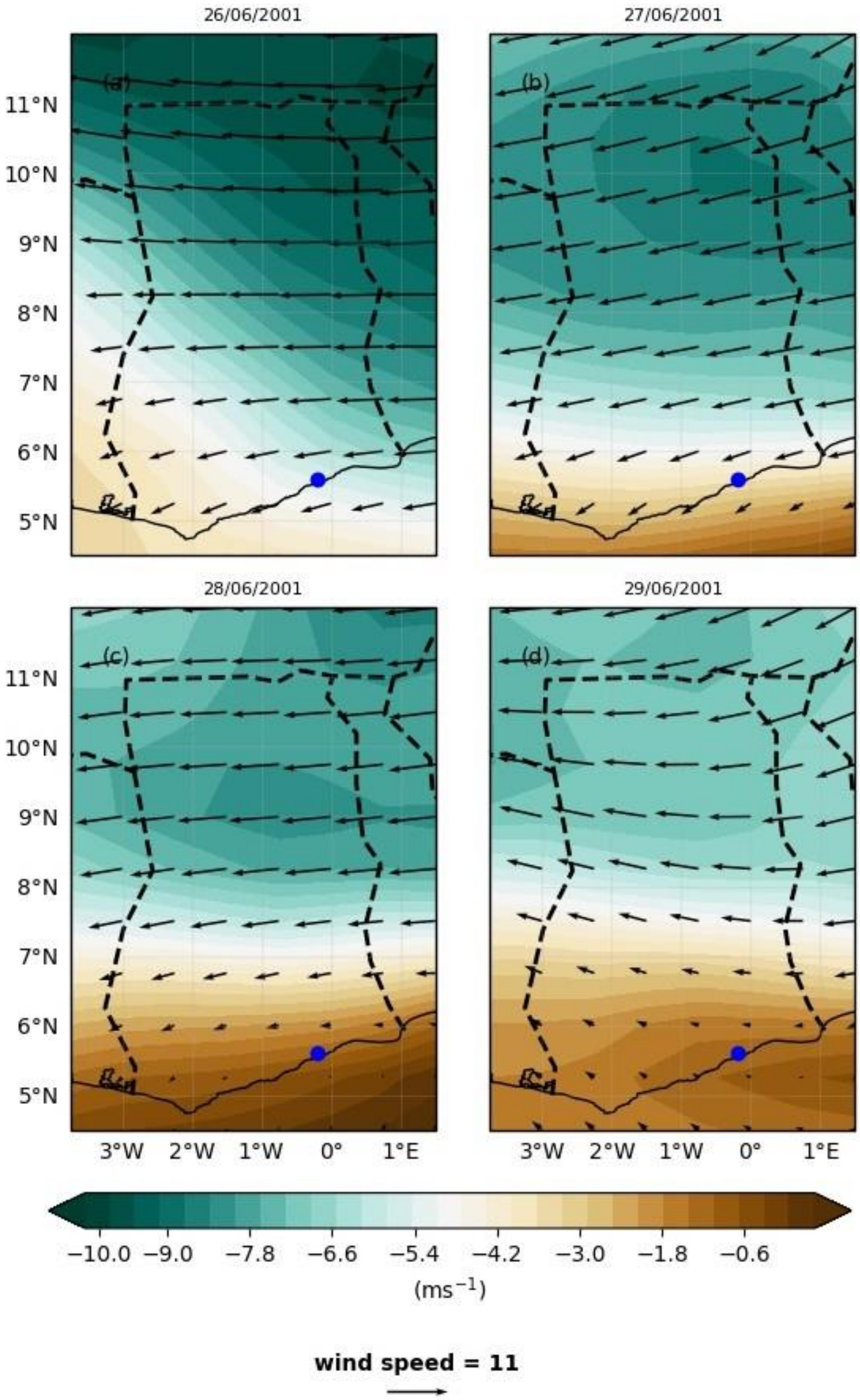

Figure 30: Horizontal Wind Velocity (shading) and an overlay for winds (vector) for entire atmosphere at 700 hPa for the Pre event days (a) 26th June, 2001, (b) 27th June, 2001 During the event (c) 28th June, 2001 and Post event day (d) 29th June, 2001.

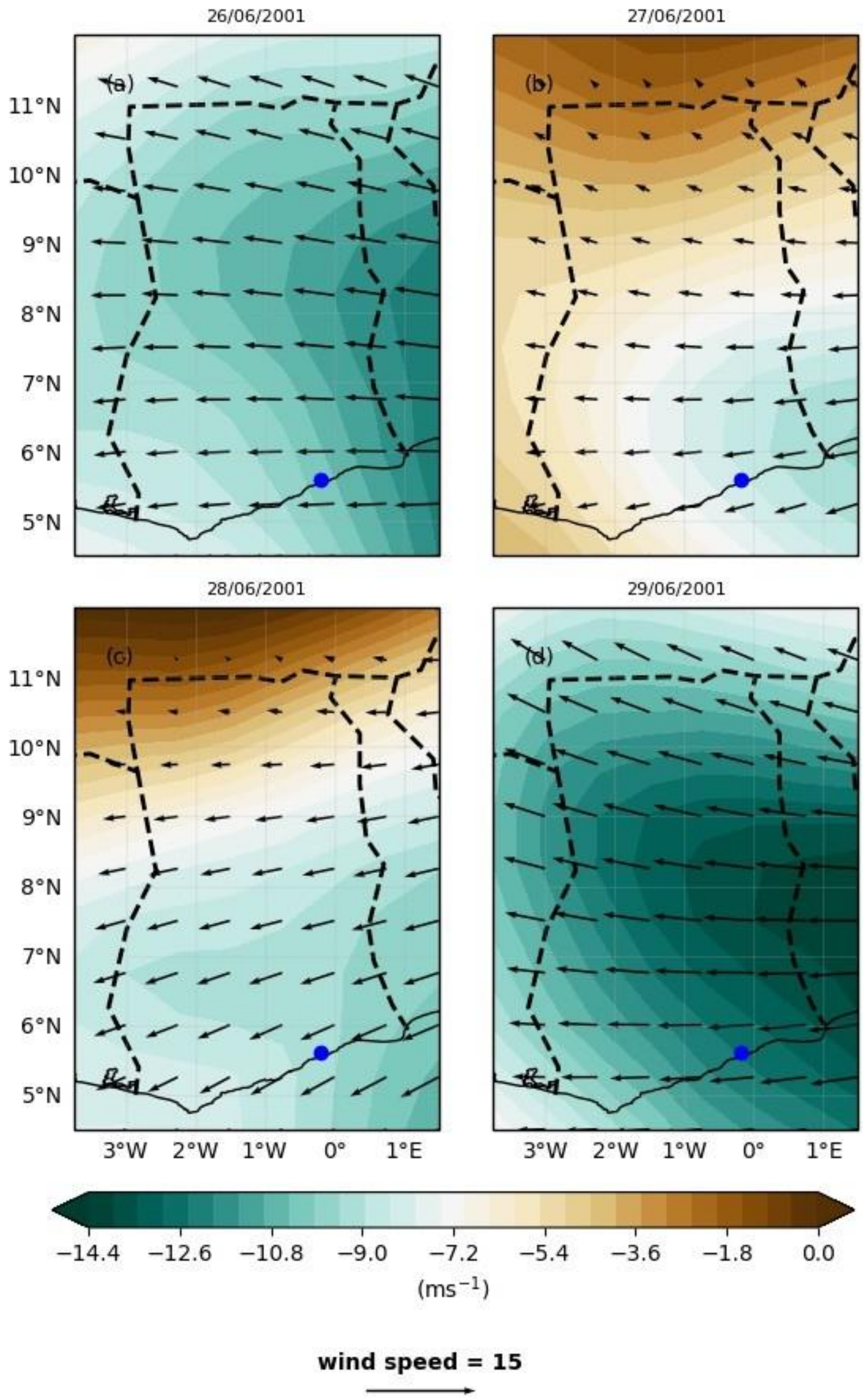

Figure 31: Horizontal wind velocity (shading) and an overlay for winds (vector) for entire atmosphere at 200 hPa for the pre event days (a) 26th June, 2001, (b) 27th June, 2001 during the event (c) 28th June, 2001 and post event day (d) 29th June, 2001.

Table 1 shows a correlation of precipitation and the atmospheric parameters considered in the study. All the parameters showed a poor Pearson correlation and coefficient of determinant (R^2) with surface specific humidity showing the highest with an R^2 of 0.378 (38%). This indicates that 38% of the variability in precipitation in Ghana can be explained by surface specific humidity.

Table 1: Correlation of Predictor with Precipitation. Variables are Averaged over the Region.

Variable	R	R^2
surface specific humidity	0.615	0.217
zonal moisture flux	0.155	0.080
zonal wind at 850 hPa	0.109	0.378
zonal wind at 700 hPa	0.0472	0.0239
zonal wind at 200 hPa	0.00633	0.0118

Chapter summary

In this chapter, the individual 95th percentile and 30th percentile for the entire historical record of each rainfall station was calculated and used as the threshold above which daily rainfall is defined as an extreme event and non-extreme event. The ERA-Interim reanalysis data is compared with observational data to assess the ability of the reanalysis to simulate synoptic circulation over Ghana. The simulated historical precipitation, surface specific humidity, horizontal moisture flux and atmospheric circulation are also investigated. What has been shown is that surface specific humidity and zonal moisture flux at 850 hPa level play an important role in rainfall variability.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Overview

This chapter presents the summary, conclusions and recommendations of the study. Whilst the summary recaps the overview of the research problem, objective, procedures, data processing and analysis and the key findings of the study, the conclusions deal with the implication of findings of the study. The recommendations present specific strategies to be implemented by policy makers based on the conclusions of the study.

Summary

The study of the dynamics and drivers of extreme rainfall in Ghana sought to assess the spatial and temporal characteristics of rainfall over Ghana with a better understanding of some mechanisms and physical processes responsible for extreme rainfall. Daily rain gauge observation and re-analysis dataset for 27 years were used for the study.

A threshold as the 95th percentile and 30th percentile at each grid point from the chronological series of 9862 values is firstly carried out. Then extreme daily rainfall is identified as precipitation exceeding the gridded 95th percentile as non-extreme daily rainfall is identified as precipitation below the gridded 30th percentile.

The spatial and temporal characteristics of rainfall over Ghana, shows that a unimodal rainfall is observed in the northern part of the country with rainfall within the months of July- September whereas the southern part experiences a bi-modal rainfall peaking in the months of June and September. This confirms the results from (Nkrumah et al., 2014; Ofori-Sarpong & Annor, 2001). Atmospheric circulations at 850 hPa is seen to be northeasterly during DJF and SON seasons and southeasterly during AMJ season. At 700 hPa, wind vectors are seen to be weak during the DJF and strong during the AMJ and SON seasons. Also, at 200 hPa, during the month of January, February and December, the dominating wind is the southwesterly. Earlier studies conducted by (Grist & Nicholson, 2001) showed that weaker African easterly jet and stronger tropical easterly jet were observed during wet years.

The presence of specific humidity is evident throughout the entire country at all seasons with AMJ having the highest intensity compared to SON and DJF, and this confirms the results from (Athar & Ammar, 2016). Approaching the dry season, the southward movement of ITD is observed to cause a reduction in the amount of humidity at the surface. The transport of moisture flux along the boundary layer at 850 hPa displayed westward transport in AMJ season, over Ghana with relatively weak westward transport during the SON season in the southern part and a stronger eastward transport in the northern part. DJF season on the other side exhibits an eastward propagation of moisture flux.

Annual precipitation trends over Ghana in general have had a upward trend using the ground-based dataset over the same period of study. Similar observation was made (Browne Klutse et al., 2013) and (Quagraine, Klutse, Nkrumah, Adukpo & Owusu, 2017). The contribution of extreme rainfall to the annual rainfall total for both major and minor rainfall season is seen to be increasing and decreasing respectively over Ghana.

The surface specific humidity distribution has relatively higher values during extreme events than non-extreme events over the study area as found also in (Hellström, 2005). Similar observations were noticed for the associated precipitation. The distinguishing feature of the winds at 700 hPa is the speed magnitudes as both extreme and non-extreme events show northeasterly wind direction. The strength of wind speed can correspond to the amount of precipitation. Also, at 200 hPa extreme events show an easterly direction throughout the study area, with non-extreme events showing different characteristics at the northern and southern parts of Ghana being a southwesterly and southeasterly direction respectively.

For the two case studies, it is keenly observed that specific humidity is relatively high during pre event days and low during the event day. After the event, specific humidity begins to increase gradually. Horizontal moisture flux is observed to have a strong eastward transport during the flood event for both case I and case II. Similar circulation pattern exists between the two case studies for level 850 hPa, 700 hPa and 200 hPa. At 850 hPa the presence of southwesterlies dominated both cases during the event day, whilst at 700 hPa strong easterlies were observed for both case I and case II. During the pre event days, relatively weak easterlies were prevailing on the event day.

A gradually increasing eastward moisture flux is observed during the pre event days through to the flood day with the event day having the most intense eastward movement of moisture.

However, this study reveals that specific humidity is the main contributor to the total precipitation over Ghana than the other contributors and on average, approximately 37% of the total precipitation comes from the surface specific humidity whereas, on average, approximately 63% precipitation arises from other sources.

Conclusions

This investigation combined daily raingauge data and historical flood information in order to assess the frequency and distribution of these events, along with a preliminary investigation into the atmospheric conditions surrounding the floods. With a focus on Ghana for April-May-June, September-October-November and December-January-February seasons, the first part of this thesis analyzed extreme events, and climate drivers to identify relationships associated with both extreme and non-extreme rainfall events. A percentile method of threshold selection was tested and it was found that this would be a better method of data selection. The trend analysis of the extreme rainfall suggests that there has been a significant increase in the annual rainfall and the contribution of SON extreme rainfall to the annual total. The drivers of extreme rainfall variability are more similar to drivers of total rainfall in the wet season than the dry season. In this study it is found that the mean wind was essentially from the south and the westerly component was the most relevant for the rain. It can be speculated that the progressive westerly wind is due to convective transport of westerly momentum from the borders into the country. Relatively high specific humidity dominates Ghana during both the wet and dry seasons, in the lower troposphere. During the wet season, the southwestern part of Ghana, records higher amounts of lower tropospheric specific humidity values. Zonal moisture flux transport components in the wet season indicate its dominance in the contributing to the formation spatial and the temporal precipitation patterns. During the extreme events, the AEJ is stronger. The seasonal cycle shows a maximum in extreme event, compared to dry season. Thus, the TEJ may be a critical factor in the intensity of rainfall of

Ghana. Climate variables, such as specific humidity and zonal moisture flux, have stronger relationships with extreme rainfall than mean rainfall. This result highlights the importance of data quality control and the significance of historical flood data to confirm the presence of floods.

Recommendations

The findings of this thesis can provide a pathway to future research topics in areas such as agronomy, ecology, geography and public policy. Future research topics could include understanding and the influence of extreme events on agriculture, what plant species and animal species are impacted by extreme events, and how their climates are changing. Lastly, this information can be used to assist policy makers in assessment of past environmental decisions and most importantly, future changes.

This project utilised raingauge data from ten regions of Ghana using a total of 22 raingauges. This method was partially successful in the identification of extreme rainfall events. However, in order to form a more complete picture of each region studied, it would be beneficial to create a gridded dataset using observations from all available raingauges in each region. The data could be combined using the 'nearest neighbour' method, or a more sophisticated data interpolation method. This would provide the density of observations required to identify some of the highly localised events.

Although efforts were made to identify as many floods as possible using historic flood records, this is a very time-consuming process and it is apparent that many events have been overlooked. Further work needs to be carried out to put together a complete historic flood record for Ghana using all available data sources.

Further studies should be carried out on teleconnections in attribution to extreme rainfall.

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APPENDIX

CODES FOR FERRET PLOTS

```
use uv_0_75_88_2014_daily_AMJ_timmean.nc

use uv_0_75_88_2014_daily_SON_timmean.nc

use uv_0_75_88_2014_daily_DJF_timmean.nc

go multi_view 3, 4, 0.17, 0.1, 0.05,  0.21, 0.2, 0.06 ppl tics,0.1,0.1,0,0

set view v11

ppl axlabp, -1, -1

fill/nolab/nokey/level=(-5,1,0.2)/palette=green_brown

u[x=4:2,y=4.5:12,d=1,l=1,k=31];go land 1 "" black

VECTOR/OVE/title="wind speed"/length= 10/nolab/L=1

u[x=4:2,y=4.5:12,d=1,k=31], v[x=-4:2,y=4.5:12,d=1,k=31]

label 2.3,12.5,0,0,0.14, @SR@P1 850 hPa

label -2,12.3,0,0,0.12, @SR@P1 AMJ

label -2.8,12.3,0,0,0.12, @SR@P1 (a)

set view v12

ppl axlabp,0,-1 ! Label only the y-axis, on the left

fill/nolab/nokey/level=(-5,1,0.2)/palette=green_brown

u[x=4:2,y=4.5:12,d=2,l=1,k=31];go land 1 "" black

VECTOR/OVE/title="wind speed"/length= 10/nolab/L=1

u[x=4:2,y=4.5:12,d=2,k=31], v[x=-4:2,y=4.5:12,d=2,k=31]

label -2,12.3,0,0,0.12, @SR@P1 SON

label -2.8,12.3,0,0,0.12, @SR@P1 (b)

set view v13

ppl axlabp,-1,-1
```

```
fill/nolab/level=(-5,1,0.2)/palette=green_brown
u[x=4:2,y=4.5:12,d=3,l=1,k=31];go land 1 "" black
VECTOR/OVE/title="wind speed"/length=10/nolab/nolab/L=1
u[x=4:2,y=4.5:12,d=3,k=31], v[x=-4:2,y=4.5:12,d=3,k=31]
label -2,12.3,0,0,0.12,@SR@P1 DJF
label -2.8,12.3,0,0,0.12, @SR@P1 (c)
label 2.3,12.2,0,0,0.12, @SR@P1 (ms^-1)
set view v21
ppl axlabp,-1,-1 ! Label only the y-axis, on the left
fill/nolab/nokey/level=(-11,-1,0.5)/palette=green_brown
u[x=4:2,y=4.5:12,d=1,l=1,k=26];go land 1 "" black
VECTOR/OVE/title="wind speed"/length= 10/nolab/L=1
u[x=4:2,y=4.5:12,d=1,k=26], v[x=-4:2,y=4.5:12,d=2,k=26]
label 2.3,12.5,0,0,0.14, @SR@P1 700 hPa
label -2,12.3,0,0,0.12, @SR@P1 AMJ
label -2.8,12.3,0,0,0.12, @SR@P1 (d)
set view v22
ppl axlabp,-1,-1 ! Label only the y-axis, on the left
fill/nolab/nokey/level=(-11,-1,0.5)/palette=green_brown
u[x=4:2,y=4.5:12,d=2,l=1,k=26];go land 1 "" black
VECTOR/OVE/title="wind speed"/length=10/nolab/L=1
u[x=4:2,y=4.5:12,d=2,k=26], v[x=-4:2,y=4.5:12,d=2,k=26]
label -2,12.3,0,0,0.12, @SR@P1 SON
label -2.8,12.3,0,0,0.12, @SR@P1 (e)
set view v23
```

```
ppl axlabp,-1,-1

fill/nolab/level=(-11,-1,0.5)/palette=green_brown

u[x=4:2,y=4.5:12,d=3,l=1,k=26];go land 1 "" black

VECTOR/OVE/title="wind speed"/length=10/nolab/L=1

u[x=4:2,y=4.5:12,d=3,k=26], v[x=-4:2,y=4.5:12,d=3,k=26]

label -2,12.3,0,0,0.12, @SR@P1 DJF

label -2.8,12.3,0,0,0.12, @SR@P1 (f)

set view v31

ppl axlabp,-1,-1 ! Label only the y-axis, on the left

fill/nolab/nokey/level=(-10,22,2)/palette=green_brown

u[x=4:2,y=4.5:12,d=1,l=1,k=15];go land 1 "" black

VECTOR/OVE/title="wind speed"/length=10/L=1

u[x=4:2,y=4.5:12,d=1,k=15], v[x=-4:2,y=4.5:12,d=1,k=15]

label 2.3,12.5,0,0,0.14, @SR@P1 200 hPa

label -2,12.3,0,0,0.12, @SR@P1 AMJ

label -2.8,12.3,0,0,0.12, @SR@P1 (g)

set view v32

ppl axlabp,-1,-1

fill/nolab/nokey/level=(-10,22,2)/palette=green_brown

u[x=4:2,y=4.5:12,d=2,l=1,k=15];go land 1 "" black

VECTOR/OVE/title="wind speed"/length=10/nolab/L=1

u[x=4:2,y=4.5:12,d=2,k=15], v[x=-4:2,y=4.5:12,d=2,k=15]

label -2,12.3,0,0,0.12, @SR@P1 SON

label -2.8,12.3,0,0,0.12, @SR@P1 (h)

set view v33
```

```
ppl axlabp,-1,-1

fill/nolab/level=(-10,22,2)/palette=green_brown

u[x=4:2,y=4.5:12,d=3,l=1,k=15];go land 1 "" black

VECTOR/OVE/title="wind speed"/length=10/nolab/L=1

u[x=4:2,y=4.5:12,d=3,k=15], v[x=-4:2,y=4.5:12,d=3,k=15]

label -2,12.3,0,0,0.12, @SR@P1 DJF

label -2.8,12.3,0,0,0.12, @SR@P1 (i)

frame/file=wind_.gif
```