Assessing Agricultural Risk in Africa Using Satellite Data and Land Surface Models

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Abstract

Droughts pose a major risk in most African countries including Ghana where agricultural activities are heavily dependent on rainfall. Efforts at assessing droughts and providing decision support tools to farmers are hampered by a lack of rainfall and other meteorological data over many parts of Africa. Satellite based rainfall measurements have been suggested to fill the rainfall data gaps over Africa to enable effective assessment of droughts. Traditional methods of assessing droughts have been based on statistical formulations that relied mostly on precipitation. This approach to assessing droughts ignores important soil water balance processes such as evapotranspiration and antecedent soil moisture which limits its applicability to agricultural drought assessment. We use in-situ observation data (OBS), satellite estimated rainfall data (TAMSAT) and the Joint UK Land and Environment Simulator model to study soil moisture and how it impacts on crop production. The response of soil moisture to changes in vegetation and soil type is tested through a series of experiments in which the soil and vegetation parameters in JULES are changed. TAMSAT was found to persistently underestimate the intensity and amount of rainfall and as a result soil moisture content over northern Ghana but showed good skill replicating the inter-annual variations and the occurrence of rainfall during the rainy season. Soils with greater clay contents showed more tendencies to have drought than those with lesser clay content. Land surfaces with C3 grass were found to be less prone to droughts than those with C4 grass. Meteorological wet and dry years were found not to correspond to agricultural wet and dry years highlighting the importance of using soil moisture for assessment agricultural drought as was done in this study.
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Chapter One: Introduction

1.1 Introduction
This study is about the risks associated with African agriculture in general with a particular focus on the northern region of Ghana. There are numerous factors that pose a risk to agriculture including pests, wildfires, droughts, excessive rainfall and wrongful application of farm chemicals (Food and Agriculture Organisation, 2012). Our main focus is on drought and how it impacts agriculture. However, the concept of drought is very broad. There are different types of droughts including hydrological, meteorological and agricultural droughts and several means to deal with each particular type of drought. Our work focuses on agricultural drought with emphasis on soil moisture deficits.

This chapter sets out to introduce the type of agricultural activities that go on in Africa, the various problems associated with it and how farmers have been dealing with those problems. African climate is also briefly discussed before shifting attention to Ghana where the study is carried out. After discussing the agro-ecological zones in Ghana, we introduce the study area by discussing its location within Ghana and why it is important to carry out this study in that part of the country. We then take a brief look at the definitions of drought and previous work done on droughts as well as some of the indices that have been used globally to assess drought. This then ties in with the motivation of the study – an attempt to reduce risk for farmers and other stakeholders in the agricultural sector through the provision of a decision support tool on droughts. The chapter concludes by giving an outline of what is to be expected in the remaining chapters of this report.

1.2 African agriculture and challenges associated with it
Agriculture in most developing countries including those in sub-Saharan Africa is heavily rainfall dependent. In most of these countries there are very few irrigation facilities (Miyoshi and Nagayo, 2006). As a result of the inadequate nature of irrigation facilities, the onset, duration and cessation of the rainfall season determine the activities of most farmers. Agricultural planning is often done to coincide with the prevailing rainfall patterns in a particular place. Farmers who live in areas with a bimodal rainfall season will usually have two growing seasons while those in areas with a unimodal rainfall season will have just one growing season. This
over-reliance on rainfall patterns for farming activities exposes farmers in African countries to considerable risks. These risks arise because the rainfall over most places is highly unpredictable with lots of intra-seasonal and inter-seasonal variation in the amount of rainfall that is obtained. The onset, duration and cessation of rainfall over any particular place are not fixed with wide variations occurring from year to year (Mugalavai et al., 2008). Dry spells within the main rainy season are also very common and this adds to the risks faced by farmers (Mupangwa et al., 2011). In some cases, excessive rainfall leads to water logging of farm lands and erosion which leads to a loss of soil nutrients and crop failure (Oenema et al., 2003).

To reduce these risks and ensure the sustainability of their farms, farmers have adopted a number of measures. This includes using local materials to make erosion check gates to prevent erosion due to heavy rainfall. Mulching as a way of reducing evaporation and keeping the soil moist is also a very common farm practice in small scale rain-fed agriculture (Adams, 1966; Ramakrishna et al., 2006).

Beyond the farming practices listed above, some farmers have also resorted to insuring their farms as a way of reducing their risk. Various measures have been taken by governmental and non-governmental organizations, NGO’s, to sensitize farmers on the need to insure their farms leading to an increase in the number of farmers taking up some form of farm insurance (http://feedthefuture.gov/printpdf/1239).

1.3 Understanding the climate of Africa

As stated in the previous section, rain-fed agriculture plays an important role in the lives of people in many countries and this is expected to continue for a long time into the future (Rockstrom et al., 2010). For many tropical countries like Ghana, rain-fed agriculture is the mainstay of the people. The success or otherwise of this type of agricultural activity depends largely on a good and reliable rainfall season. Global climate change is expected to have impacts on the rainfall seasons of the tropics. The onset, duration and cessation of the rainfall seasons are expected to get increasingly unpredictable as the climate of the tropics change (Feng et al., 2013). The Intergovernmental Panel on Climate Change, IPCC, projects droughts and other extreme weather events such as flooding to be more prevalent in the coming decades (IPCC,
Such changes in rainfall patterns and amount will have impacts on rain-fed agriculture with potentially devastating effects on farmers in general and small scale subsistence farmers in particular.

The potential impacts of changes in rainfall patterns require greater efforts at understanding the weather of the tropics in order to increase the adaptive capacity of people dwelling in the tropics. Considerable progress has been made in gaining scientific understanding of the weather in some tropical areas such as the Indian monsoon (e.g., Kumar et al., 1999; Gadgil, 2003; Rajeevan et al. 2006) and the Australian Monsoon (e.g., Bowman et al., 2010 and Berry et al., 2012). African weather and climate however is not fully understood despite some concerted effort to learn about the processes that affect weather over that region. For instance, the African Easterly Wave (AEW), which is one of the factors that affect the strength of the West African Monsoon, WAM, is not properly understood (Hall and Peyrillé, 2006). This problem is compounded by a lack of meteorological data from Africa for research. For example, in a 2013 report on the climate of Africa, the World Meteorological Organisation, WMO states that “it was not possible to assess the annual average total precipitation over the continent” because adequate long term precipitation data was not available (WMO, 2015). As shown in figure 1.1, the network of weather observing stations is sparse and even where there is data it is usually not quality-controlled and not in user-friendly format. Several efforts have been made by the scientific community to correct this lack of data. These efforts include the African Monsoon Multidisciplinary Analysis, AMMA project which setup several radiosonde (Upper Air) and surface observing stations across the West African sub-region (see Radelsperger et al., 2006; Parker et al., 2008, Fink et al., 2011).
The lack of data in Africa and other parts of the world as shown in figure 1.1 poses a problem to researchers but these challenges can be partially overcome with the use of satellite data. Satellite data has many advantages over manned surface weather stations. Key among these advantages is its availability over all parts of the world in a continuous manner. Also, because satellite measurements are automated, it is less prone to data entry errors often found in meteorological data from manned weather stations. The temporal resolutions of most satellites allow for data to be collected at intervals of 15 to 30 minutes compared to synoptic observations which are done on hourly basis. Satellite data is thus easily available and ready to use and therefore in areas where there are no manned or automatic weather stations, satellite data is often used as a substitute.

In spite of the advantages associated with satellite estimated data, there some challenges with its use. One of the major drawbacks to the use of satellite data is that there is not enough historical satellite datasets available. This is mainly because it was not until the late 20th century that satellite technology became available on a wide scale. Another challenge stems from the fact that Satellites use remote sensing techniques to obtain data and are therefore prone to systematic
errors being introduced in the measurements (Salby and Callaghan, 1997; Yang et al., 1999). For example, satellites cannot observe below certain types of clouds and thus surface temperature data obtained on cloudy days may be prone to errors.

Several datasets have been developed based on satellite estimates and rainguage data have been developed for use over Africa. These include the Tropical Rainfall Measuring Mission (TRMM 3B42) (Kummerow et al., 2000), Climate Prediction Center Morphing method (CMORPH) (Joyce et al., 2004) and TAMSAT African Rainfall Climatology and Time series (TARCAT) (Maidment et al., 2014).

The Tropical Applications of Meteorology using SATellite, TAMSAT project has been at the forefront of using satellite estimated rainfall data to fill in the gaps over Africa. TAMSAT has been particularly successful at using satellite estimated data to fill in the data gap over most of Africa even though it has problems with underestimating intensity and amount of rainfall (e.g. Thorne et al., 2001; Asadulah et al., 2008; Maidment et al., 2014).

1.4 Impacts of droughts on agriculture

There is no universally accepted definition of drought but for this work we will adopt the National Disaster Mitigation Centre’s, NDMC (2008), definition of drought which is an “extended period - a season, a year, or several years - of deficient precipitation compared to the statistical multi-year average for a region that results in water shortage for some activity, group, or environmental sector”. Droughts are usually caused by lack of or reduction in rainfall but human activities such as the construction of a dam upstream of a river can cause droughts downstream of the river. There are different types of droughts. These include meteorological droughts, agricultural droughts, hydrological droughts and socioeconomic droughts. Meteorological droughts are usually defined relative to an average of the long-term precipitation records (at least 30 year period). The average of the this long-term precipitation records is considered a ‘drought line’. Any year in which precipitation falls below the average is then considered a drought year. Agricultural drought occurs when there is insufficient soil moisture to meet the needs of particular crops at a particular time (FAO, 2012). Insufficient moisture at the top levels of the soil to support crops during the germination stage can be considered an
agricultural drought even though there may be enough moisture at lower levels of the soil. When reduced precipitation leads to reduced water availability and this has adverse effects on human activities, then a socioeconomic drought is said to have occurred (WMO, 2005).

Droughts are a common feature of African climate and there have been several studies to understand them from meteorological, agricultural, and food security perspectives (Shahanan et al., 2009; Calow et al., 2010). Droughts in Africa can last for periods ranging from a single year like the 1984 drought in the east African region (Downing et al., 1989), or for several years like that which occurred in the Sahel region of West Africa between 1968 and 1973 (Glantz, 1988). Using rock sediments from Lake Bosumtwi in Ghana, Shahanan et al., (2009) showed that droughts lasting for decades have been a common feature of West African Climate for at least the last three millennia.

Drought and variability in rainfall have long been known to be major risks to agriculture worldwide. The most recognisable impact of drought on agriculture is a fall in crop production. Droughts also lead to a reduction in pasture production and the availability of water for animal consumption and thus adversely affect animal production. For small scale rain-fed farmers in particular, the effects of droughts can be very devastating. This is because in most tropical countries where small scale rain-fed agriculture is practised, there is little or no irrigation facility to support farmers during periods of reduced rainfall (Miyoshi and Nagayo, 2006). Droughts therefore lead to crop failure which means these farmers do not get enough farm produce to feed their families or sell to meet other needs. This leads to other consequences such as their children dropping out of school and increasing interest rates on loans for those farmers who contract loans to operate their farms.

1.5 Traditional Drought Indices

Due to the devastating effects of droughts on farming activities and socioeconomic life, lot of effort has gone into providing forecasts and indices to aid farmers and governments in their decision making process. At the global level, several drought indices have been developed. These include Percent of Normal, Palmer Drought Severity Index (PDSI) (Palmer, 1965), Surface Water Supply Index (SWSI) (Shafer and Dezman, 1982) and Standard Precipitation
Index (SPI) (McKee et al., 1993). The most widely used of these indices are the Palmer Drought Severity Index and the Standard Precipitation Index.

PDSI is based on precipitation and temperature data and the Available Water Content (AWC) of the soil. It was developed by Palmer (1965) to measure the departure of moisture supply from normal (average) conditions at a specific location. The PDSI is based on the water balance equation, specifically the supply and demand side of the water balance equation. PDSI varies between -6.0 and +6.0 with values below -4 representing extreme drought while values exceeding +4 are extreme wet. Values of the PDSI between -0.49 and +0.49 are considered normal. For a full description of all the drought and wetness classifications of the PDSI, please refer to Palmer (1965) or (WMO Doc 8, 2005).

The PDSI though very useful has some limitations. For instance, Alley (1984) and Karl and Knight (1985) have done extensive studies on the PDSI and have pointed out that the values quantifying the intensity of drought, the beginning and end of a drought or wet spell and how they were characterised by Palmer were arbitrarily selected and have little scientific meaning. Another problem with the PDI is that it does not take snowfall, snow cover, and frozen ground into the calculation of the index. This limits the applicability of the PDI during winter and over surfaces that are covered with ice. One more problem associated with using the PDI is that it is location specific due to its reliance on available water content of a particular place in the calculations. Also, McKee et al. (1995) showed that even though the PDSI is designed for agriculture, it is unable to accurately assess the hydrological impacts of longer lasting droughts. Despite these limitations, the PDSI is widely used for drought planning around the world and is very popular in the United States of America.

The SPI is based on long-term precipitation only and has been designed to calculate precipitation deficits for multiple timescales. The original calculations of the SPI from McKee et al (1993) were for periods of 3, 6, 12, 24, and 48 month time scales (WMO Doc 8, 2005). However due to its flexibility, calculations of the SPI can be made for different time scales that a user requires. Precipitation does not follow a normal distribution and therefore the SPI calculations are fitted to a gaussian distribution with zero mean and unit variance (Edwards and McKee 1997). This way, wet and dry periods can be analyzed in the same manner. The SPI like the PDSI has a range of
values which indicates the severity of a drought or the level of wetness of a place. Its values range from less than -2 to greater than +2, representing extremely drought and extreme wetness respectively. An SPI value between -0.99 and +0.99 is considered normal. The rest of these SPI values and their interpretation can be found in McKee et al (1993) and (WMO Doc.8, 2005). The major deficiency with SPI calculations is that is based on only precipitation and does not take into account evapotranspiration and potential evapotranspiration which are key components of soil water balance (WMO Doc 8, 2005). SPI has also been found to underestimate the wetness/dryness for very low/very high rainfall events (Kumar et al., 2009).

Efforts have been made to improve upon these drought indices in order to make them more useful for agricultural purposes. Ntale and Gan (2003) made changes to the PDSI’s formula taking potential runoff into consideration and reported improved results for drought monitoring in East Africa. The SPI has also been modified by NCAR to take into account potential evapotranspiration in what is called Standardized Precipitation evaporation Index (SPEI) with improved results in the ability to assess drought (NCAR, 2015).

1.6 Agro-Ecological Zones and Climate of Ghana

The Republic of Ghana lies within latitude 4° 44’N - 11° 11” N and 3° 11’W - 1° 11” E making it a tropical country. Ghana’s current population is estimated at about 25 million people out of whom 62 percent live in urban areas with the remaining 38 percent living in rural areas. The latest data from the Ghana statistical service, GSS (2014), shows the services sector has the greatest contribution to the Ghana’s gross domestic product, GDP, with 49.5 percent followed by industry at 28.5 percent. Even though the share of agriculture in the GDP of Ghana has been reducing over the years, it comes in third with a contribution of 22 percent (Ghana Statistical Service, 2014). Crops, however, remain the largest activity in the agriculture sector, contributing about 17 percent of GDP. The crops grown in Ghana are made of cash crops like cacao, fresh tropical fruits like mango and pineapples, cereals like maize and rice, roots and tubers like yam and cassava among others.
Based on natural vegetation and climate, Ghana is divided into six agro-ecological zones. These agro-ecological zones from north to south are: Sudan Savannah Zone, Guinea Savannah Zone, Transition Zone, Semi-deciduous Forest Zone, Rain Forest Zone and the Coastal Savannah Zone (FAO, 2005). The southern half of Ghana has a bimodal rainfall pattern allowing for two annual growing seasons (major and minor growing seasons) (Oppong-Anane, 2006). Unlike the south, the northern half of Ghana has a unimodal rainfall season, allowing for only one growing season. The period between the rainy seasons is characterized by hot, dry continental winds that blow from the northeast across the Sahara desert and into Ghana causing hot, dry days, and cool nights (Oppong-Anane, 2006). This period is also known as the Harmattan period or the dry season.

These rainfall patterns (seasons) of Ghana can be explained mainly by the position and movement of the Intertropical Convergence Zone, ITCZ. Over West Africa, the ITCZ is broadly considered as a confluence region for trade winds from the two hemispheres of the earth (Hastenrath, 1991). These trade winds are the dry north easterly trade winds from the Sahara Desert and the moist south-westerly trade winds from the Atlantic Ocean. The ITCZ follows the seasonal movement of the sun and is usually located in a region of maximum solar heating (Schneider et al., 2014). As a result of its co-location with the region of maximum solar heating, the ITCZ is associated with low pressure which allows for the formation of intense convective systems such as squall lines and thus heavy precipitation (Hourdin et al., 2010, Schneider et al., 2014). The movement of the ITCZ over Africa during the year is shown in figure 1.2 below. Beginning in March, the ITCZ moves north of the equator following the movement of the sun during the northern hemisphere summer. This northward movement of the ITCZ allows moisture laden south-westerly wind from the Atlantic Ocean to push inland into most parts of West Africa. The influx of moisture coupled with the heating from the sun leads to the development of convective systems and this period is known as the West African Monsoon period (Cornforth, 2013; NOAA Climate Prediction Centre; 2015). This monsoon starts from the southern coasts of West Africa and gradually moves north. The ITCZ reaches its northernmost point in September. When the ITCZ moves south during the southern hemisphere summer, there is an influx of dry, dusty winds from the Sahara Desert into West Africa leading a dry season also known as the Harmattan (Schwanghart and Schütz, 2008). This southward movement of the ITCZ begins in
October and the ITCZ reaches its southernmost point in February. The harmattan, starts from the northern parts of West Africa and gradually moves downwards towards the south.

For some years, the movement of the ITCZ does not follow the patterns described in figure 1.2 leading to inter-annual and intra-seasonal variability in rainfall over the West African region including Ghanaian (Taylor, 2008).

![Figure 1.2: Monthly position of the ITCZ over Africa (solid white line). Arrowed lines show the direction from which the winds are blowing. (Source: The Comet Program/NOAA).](image)

**1.7 The study area**

The study is conducted for the northern and upper east regions of Ghana in West Africa (figure1.3). Specifically, we will focus on Tamale (0930N, 00051W) in the northern region and Navrongo (1054N, 00106W) in the Upper East region of Ghana. With a total land size of 79,226 square kilometres and a population of about 4 million people, these two regions constitutes 34 percent of the land area (Figure 1.3) and 16% of the population of Ghana respectively (Ghana Statistical Service, 2014). Like most parts of Ghana, rainfed agrigulcutre is the mainstay of the people. The Ghana Statistical Service (2012) estimated that farmers make up 68.5% of the total population in this part of Ghana. This is above the national average of 56%. Of an estimated 8745 hectares of irrigated farmlands in Ghana, approximately 3500 hectares is in the northern regions (Miyoshi and Nagayo, 2006). For farmers in Northern Ghana, the start of the rains also coincides with the start of the growing season (Yengoh et al., 2010). However, Antwi-Agyei et
al., (2012) showed that due to the low income levels in the three northern regions of Ghana, farmers in those regions were more vulnerable to the effect of droughts and climate change and variability. Roots and tubers, rice, maize, and other cereals are the main food crops grown in the northern parts of Ghana. In addition to these crops, animal rearing is also an important farming activity for the people. The vegetation of the northern Ghana is one of savanna grassland with clusters of drought-resistant trees such as baobabs or acacias.

Figure 1.3: Map of Ghana with the location of the study area in green.

1.8 Motivation for the study

Rainfed agriculture is one of the key economic activities of the people of Ghana. However rainfall on its own is not the most important factor in the production of crops. Rather, it is the water in the ground that crops depend on for growth and which will eventually determine the
success or otherwise of the farmers in northern Ghana. Periods of prolonged drought have often led to famine in many parts of the world. Records of the devastation caused by droughts abound (http://www.telegraph.co.uk/news/worldnews/africaandindianocean/somalia/8647089/Factbox-Famine-in-Africa.html). Record low rainfall led to over a million deaths in Ethiopia in between 1984 and 1985. In Sudan, an estimated one hundred thousand people lost their lives as a result of droughts in 1989. As recently as 2005, more than a quarter of the population of Niger needed urgent food aid following a year of drought. Ghana has also had problems with droughts in the recent past. 1983 stands out in the memory of most adult Ghanaians as a particularly bad year because most farmers lost their crops due a drought that was experienced across the West African Region (Ofori-Sarpong, 1986; Masih et al., 2014). Several research projects have been undertaken on the rainfall patterns and its variability over Ghana in general (e.g Amekudzi et al., 2015,) and the northern region in particular(e.g Nkrumah et al; 2014). However not much has been done to quantify the relationship between rainfall and soil moisture in Ghana. Research seeking to deal with drought and uncertainty in rainfall in Ghana has mainly focused on the onset, duration and cessation of the rainy season because this is of more importance for agricultural purposes. For example, Antwi-Agyei et al., (2012) using rainfall data and on-site interviews looked at how changes in the onset, duration and variability in the rainfall seasons impact on the lives of Ghanaian farmers and reported that uncertainty in the onset and cessation of rainfall increased risks for farmers in Ghana. Yengoh et al., (2010) also looked at trends in agriculturally relevant rainfall for Ghana and found that dry spells within the rainy season was the main factor that affected agricultural production. However, knowing the onset, duration and cessation of rainfall over a particular place in itself does not do much to reduce the risks associated with rain-fed agriculture. This is because the amount of rainfall available for use by plants is affected by other factors such as evapotranspiration, soil type among others. Additionally, as noted by the IPCC (2013) and other research findings, rainfall patterns are changing and with it the seasons and intensities of rainfall events, as a result of global climate change. Dry-spells within rainfall seasons are also becoming more frequent.

One of the deficiencies of the existing drought indices is that they are based on precipitation and quantifies droughts in terms of deficits in rainfall. Crops depend on moisture in the soil and the assumption in these indices is that higher rainfall means more water being available for crop
production. However, other factors such as soil type, evapotranspiration/potential evapotranspiration rate and surface run-off rate create a non-linear relationship between rainfall rate and soil moisture. Unfortunately in the generation of indices like PDSI and SPI, some of these factors like soil type and land surface cover are not taken into consideration.

1.9 Aim of the study

The aim of this study is investigate the possibility of using soil moisture as a basis for defining agricultural droughts through the use of a Land Surface Model as well as possibility of using satellite estimated rainfall data for drought assessment in Ghana.

1.10 Research Questions

The key questions that we seek to answer in this study are;

• how do TAMSAT rainfall estimates compare to the rain-gauge data?
• can TAMSAT rainfall estimates be used for soil moisture monitoring and drought assessments?
• is a meteorological wet/dry year the same as an agricultural wet/dry year?
• what is the sensitivity of soil moisture to vegetation type and to soil type?

1.12 Structure of the report

The remainder of this report is organised into 5 chapters as follows;

Chapter 2 is about the models and methods used in the study. It is divided into three main subsections. Section 2.1 gives a description of the model that was used for this study. This includes the type of forcing data used, the structure of the model and the model outputs. Section 2.2 talks about the two sources of data used in the study namely in-situ weather observation data and TAMSAT data. Finally section 2.3 gives a background of the mathematics and the methods
behind the experiments. Chapter 3 is the first part of our results. Section 3.2 shows the seasons while section 3.3 concentrates on the annual rainfall records for Tamale and Navrongo. The assessment of how well TAMSAT replicates OBS rainfall is done in section 3.3 by comparing annual and seasonal TAMSAT rainfall to that of OBS. The chapter ends with a look cumulative rainfall for Tamale and Navrongo. The second part of the results is presented in chapter 4. Section 4.1 introduces the concepts in the chapter followed by 4.2 which looks at the response of soil moisture to the start and end of the rainy season. Section 4.3 is about the soil moisture both within the entire soil column and also at the top of the soil. Here we relate the rainfall for individual years to the soil moisture for those years. In sections 4.4 and 4.5, the effects of vegetation cover and soil type on soil moisture and how that impacts the moisture available to plants is presented. The chapter concludes by testing our results against the results of SPI calculations using the same datasets and then provides summary tables that show these results at a glance. A discussion of the key results from the experiments is made in chapter 5. Concluding thoughts about the entire study as well the limitations the study and some recommendations for future work is given in chapter 6.
Chapter Two: Model, Data and Methods

2.1 Introduction

This chapter is divided into three parts. The first part looks at model that we used in the study, the second part is about the data and the third part focuses on the methods employed.

A full description of the Joint UK land and Environment Simulator (JULES) model is available on the JULES website (https://jules.jchmr.org/model-description) and also from Best et al., 2011 and Clark et al., 2011. While Best et al 2011 deals with the energy and water fluxes in JULES, Clark et al., 2011 concentrates on carbon fluxes and vegetation dynamics of the model. The description of the model will therefore be limited to those parts that were considered relevant to this study namely the types of surfaces that can be represented in JULES, the structure of a gridbox in the model and how the movement of moisture through those layers is controlled. The outputs that will be used for the results sections of this report among others will also be discussed.

The data section describes the meteorological datasets that were used in this study and the data processing that was done in order to get the data into a model-friendly format. Two datasets were used in the study. The first of these is historical in-situ weather observation data covering the period 1970-2011 from the Ghana Meteorological Agency’s weather stations in Tamale and Navrongo. The second dataset is from The Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT), and covers the period 1983-2011.

The last part of this chapter looks at the methods in this study. This includes the definition of drought used for the study, the definitions of meteorological and agricultural wet and dry years and the statistical methods employed in the study.
2.2 Model

2.2.1 Description of JULES

Land surface models (LSM’s) serve as the lower boundary conditions with which Global Circulations MODELS (GCM’s) are run. The Joint UK Land and Environment Simulator (JULES) is the land surface scheme of the UK Met Office Unified Model (UM) (Slevin et al., 2015). JULES evolved from the Met Office Surface Exchange Scheme, (MOSES) (Clark et al., 2011). JULES can be used as a stand-alone model (offline mode) or as part of an operational weather forecasting model or global circulation models (online mode) (Best et al., 2011). The flexibility of JULES allows it to be used to model processes such as photosynthesis, evapotranspiration, soil and snow physics, among others (examples available in Blyth et al 2011, Tsarouchi et al., 2014).

For this work, JULES version 3.3 was used in the offline mode.

Figure 2.1: A schematic diagram describing a grid-box in JULES. The diagram shows the nine surface types that can be represented in JULES from left to right; broad-leaf trees, needle-leaf trees, C3 grasses, C4 grasses, urban, water, bare soil and land-ice. It also shows the four layers of soil represented in JULES from top to bottom; 0.1m, 0.25m, 0.65m, 2m (Source: https://jules.jchmr.org/model-description)
Nine different surface types of different fractional coverage can be represented in each grid box (figure 2.1). These nine surface types comprise five vegetated Plant Functional Types (PFT’s): broad-leaf trees, needle-leaf trees, C3 grasses, C4 grasses and shrubs and four non-vegetated: urban, water, bare soil and land-ice (Best et al., 2011; Clark et al., 201; Tsarouchi et al., 2014). With the exception of land-ice, a land grid-box can be made up from any mixture of the other surface types. Users are free to change these surface types to meet their particular needs.

The meteorological variables required for driving JULES are; air temperature, precipitation, wind speed, air specific humidity, long wave outgoing radiation, shortwave incoming radiation, and air pressure (Best et al., 2011). The precipitation could either be rainfall or snowfall or both but they must be specified separately (Tarnavsky et al., 2014). Some of these variables are measure directly for example rainfall, wind speed and air pressure. Others are derived from other variables for example long wave outgoing radiation, shortwave incoming radiation which are derived from solar radiation measurements and sensible heat fluxes.

The soil in a grid-box in JULES (figure 2.1) is divided into four layers. These layers are 0.1meters, 0.25meters, 0.65meters and 2meters from top to bottom respectively. Thus, a total of 3meters of soil depth is represented in JULES. The transport of soil moisture between these four layers is done numerically. This numerical solution may result in some layers becoming supersaturated while other layers remain dry. To prevent this from occurring, JULES uses two methods. The first method deals with supersaturation of lower layers such that soil moisture is prevented from infiltrating into a supersaturated layer from the top. Once a lower layer becomes supersaturated, the soil moisture in that layer is limited to the saturation point and no excess water is allowed to move into that layer. The result is that excess water is moved back up a layer. If the top layers are also supersaturated, then the excess water is added to the surface runoff.

The second method deals with super-saturation of layers at the top. In this case, the soil moisture if made to infiltrate into the soil layers below. The assumption here is that initially, soil moisture will flow laterally over the saturated layer as runoff but will eventually move down to other soil layers through “fractured permafrost or less compacted/faster draining soil types” (Best et al., 2011). In this way, excess soil moisture moves down to fill the other soil layers until all four
layers have reached super-saturation. Once all the soil layers have reached super-saturation, any excess moisture is added to the surface runoff.

### 2.2.2 JULES Vegetation Types

In this study three vegetated surfaces and one non-vegetated surface type are used. The vegetated surfaces are covered with varying percentages of Broad leaf trees (BT), C4 grasses and C3 grasses. The non-vegetated surface used is baresoil (BS). These surface types have been chosen to reflect the vegetation of northern Ghana - savanna grassland with clusters of drought-resistant trees such as baobabs and acacias (Oppong-Anane, 2006). As discussed in the model description section (section 2.1), JULES allows for various fractions of these plant functional types to be used in one model run. Table 2.1 gives the names of the various surface configurations that were used in this study and the fractions (percentages) of C4, C3, broad leaf and bare soil in each configuration.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>% of C4</th>
<th>% of C3</th>
<th>% of BT</th>
<th>% of BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>100C4</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>75C4</td>
<td>75</td>
<td>0</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>50C4</td>
<td>50</td>
<td>0</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>50C4*</td>
<td>50</td>
<td>20</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>100C3</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>75C3</td>
<td>0</td>
<td>75</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>50C3</td>
<td>0</td>
<td>50</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>50C3*</td>
<td>20</td>
<td>50</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table 2.1:** Vegetation types used in JULES experiments and the fraction of C4, C3, BT and BS present in each surface type.

By these configurations listed in table 2.1, a vegetation named 100C4 has the entire land surface covered with C4 crops and no other crop or tree is available on the soil. Similarly, a 50C3 surface has 50 percent of the land surface covered with C3 crops, 20 percent covered with BT, 10 percent is covered with BS and the remaining 20 percent is C4 grass. Two vegetation cover types have been chosen to represent a situation where a farmer decides to do mixed cropping involving C4 crops and C3 crops. These are denoted in table 2.1 as 50C4* and 50C3*. 
Two of the main crops grown in the northern region of Ghana are rice and maize. Rice is a C3 grass while maize is a C4 grass. These two types of grass have varied characteristics in how they utilize soil moisture, sunlight among other variables needed for crop growth. Most farmers alternate between the types of crop grown in a particular year. A farmer may plant rice in one year and follow it with maize the following year or vice-versa. Experiments were done for both types of crops by changing the surface type in JULES as indicated in table 2.1 above. This way, it will be possible to assess droughts for both types of crops. The version of JULES used in this study (JULES version 3.3) does not allow for the explicit representation of crops in the model (Slevin et al., 2015). Rather crops are represented as grasses. As a result reference will be made variously to C3 and C4 as crops, grasses or plants. Grasses, plants and crops as used in the rest of this study should be considered as referring to the same thing. For ease of reference, for the results and discussion chapters, these vegetative cover scenarios will be referred to by the percentage of the dominant crop (grass) type for example a vegetation type with 75 percent C3 will be referred to as 75C3.

### 2.2.3 JULES Soil Types

The International Satellite Land Surface Climatology Project, Initiative II (ISLSCP II) soil texture map (Scholes and Brown de Colstoun 2011) has the required soil parameters for Navrongo and Tamale based on the sand, silt and clay fractions for Northern Ghana. This dataset is limited at 1°x1° (100km X 100km) resolution. To be able to account for the different soil properties in the study area and to increase the usefulness of the results, experiments with four different types of soils were conducted. The first of these soil types is the original soil type that comes with JULES which is denoted as O in table 2.2 below. The other three soil types are Sandy Loam (SL), Loamy Sand (LS) and Clay Loam (CL). These soil classifications are based on the fractions of sand, silt and clay in the soil. Table 2.2 below, gives the percentages of sand, silt and clay in each soil type used in our experiments.

<table>
<thead>
<tr>
<th>TYPE OF SOIL</th>
<th>% OF SAND</th>
<th>% OF SILT</th>
<th>% OF CLAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loamy Sand (LS)</td>
<td>82</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Sandy Loam (SL)</td>
<td>58</td>
<td>32</td>
<td>10</td>
</tr>
<tr>
<td>Clay Loam (CL)</td>
<td>32</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>Original (O)</td>
<td>62</td>
<td>27</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 2.2: Types of soil used in JULES experiments and the percentage of sand, silt and clay in each soil type. (Credit: Matt Brown)
2.2.4 JULES Output

There are more than 100 variables that could be obtained as outputs from running JULES. For each variable, the user can decide whether to output the instantaneous or snapshot value (S), time mean value (M), time minimum value (N), time maximum value (X) or the accumulation over time (A). A comprehensive list of all the variables that are available for output from JULES can be found on the JULES website (http://jules-lsm.github.io/vn4.3/output-variables.html). All outputs used in this work are Time Mean Values (M). This means that for daily outputs, the values obtained will be the mean value for each day of the year. The same applies to monthly and annual outputs.

Our main focus is on agricultural drought and soil moisture is the main factor in determining agricultural drought (FAO, 2012). Therefore we set up our JULES output to obtain soil moisture for each of the four soil layers described in section 2.1 above. For the generation of the soil moisture drought index, outputs of soil moisture availability factor, Beta (β), was used. Soil Moisture availability factor, beta, is used for the assessment of agricultural drought rather than rainfall because not all the rain that falls on a particular land surface will be available to plant.

In JULES, the ability of vegetation to access moisture at each of the four levels in the soil is determined by root density. This root density is assumed to follow an exponential distribution with depth (Best et al., 2011). The mathematical formulation of beta as shown in Best et al., (2011) is now provided below.

The fraction of roots in soil layer k extending from depth $Z_{k-1}$ to $Z_k$ is

$$ r_k = \frac{e^{-2Z_{k-1}/dr} - e^{-2Z_k/dr}}{1 - (e^{-2Z_t/dr})} $$  

$eq1$

Taking transpiration $E'$ into account, the flux extracted from soil layer k is $e_k^0 E'$, where

$$ e_k^0 = \frac{r_k \beta_k}{\sum kr_k \beta_k} $$  

$eq2$
Soil moisture availability factor for soil layer $k$, $\beta_k$, is defined as

$$\beta_k = \frac{\theta_k - \theta_w}{\theta_c - \theta_w} \quad \text{eq3}$$

where $\theta_k \geq \theta_c$, $\theta_w < \theta_k < \theta_c$, and $\theta_k \leq \theta_w$

Where $\theta_k$ is the volumetric unfrozen soil moisture concentration of layer $k$, $\theta_w$ is the volumetric soil moisture concentration at wilting point and $\theta_c$ is the volumetric soil moisture concentration at the critical point. $\theta_k$, $\theta_w$ and $\theta_c$ have units of m$^3$m$^{-3}$ and therefore soil moisture availability factor is dimensionless. Beta is therefore a measure of the soil moisture stress on plants during photosynthesis. Beta has a maximum value of unity and a minimum value of zero. Zero beta means that there is no moisture available for plant photosynthesis and therefore a high soil moisture stress while a beta value of 1 means there is enough moisture to support plant photosynthesis and therefore there is no soil moisture stress on the plants.

2.3 Data

2.3.1 Synoptic Weather Observations Data (OBS)

The data used to drive JULES was obtained from the Ghana Meteorological Agency’s synoptic weather stations at Tamale and Navrongo with WMO reference numbers 65418 and 65401 respectively. These are manned stations that do hourly observation of all meteorological parameters according to WMO standards and procedures (example WMO-No.544, 2003 and WMO-No.8, 2008). The data available from the stations dates back to the 1960’s. However, for this report, 42 years’ data spanning the period 1970-2011 was used. The parameters obtained from the station include rainfall, surface pressure, atmospheric temperature, and wind speed and direction; key variables needed for running JULES. While some of these variables such as surface pressure and atmospheric temperature can be used directly as driving data for JULES, the rainfall had to be processed into model-friendly versions. This involved using stochastic methods.
to disaggregate the rainfall data from daily to hourly data. The methods used will be described under the TAMSAT datasets because similar methods were employed for both OBS and TAMSAT data.

### 2.3.2 Satellite Estimated Rainfall Data (TAMSAT)

The Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT) programme provides near real time satellite-based rainfall estimates for all of Africa. The TAMSAT method assumes that at a given location, the quantity of rainfall can be calculated from the length of time the cloud top has been above a height threshold (or below the corresponding temperature threshold). This length of time is the Cold Cloud Duration or CCD. CCD can be derived from satellite imagery. TAMSAT uses data from Meteosat Thermal InfraRed (TIR) channels to determine the ‘Cold Cloud Duration’ (CCD). Rain gauge data is then used to calibrate the rainfall estimates obtained from CCD. This method of estimating rainfall has the most skill for convective rainfall events where cloud tops can reach high into the troposphere and can be cold enough to reach the threshold needed for CCD calculations. Warm rainfall events such as that which occurs from stratified clouds are poorly estimated by CCD measurements.

TAMSAT datasets date back to 1983 and currently exists in daily, ten-daily (dekadal), monthly, seasonal and yearly forms. The datasets used for this study was daily rainfall estimates for Tamale and Navrongo for the period 1983-2011.

As mentioned earlier, JULES runs with hourly data. Therefore the daily TAMSAT data was disaggregated to hourly rainfall data. This hourly disaggregated rainfall data from TAMSAT was then used to replace the rainfall column in the JULES driving data. All the other JULES driving parameters remained the same. The methods used for rainfall disaggregation from the 3-hourly to hourly time step involved two key assumptions. Both assumptions are based on the fact that rainfall for Tamale and Navrongo is mainly convective. The first is to assume that the rainfall rate is the same for each hour of a given 3-hourly rainfall period. The second assumption is that three times the rainfall rate occurs in the middle hour of a given 3 hour period. Stochastic methods were then used to spread total rainfall for the 3 hour period to cover the entire 24 hours.
following the rainfall generator with poisson process. The computer code for the disaggregation of all meteorological data was provided by Elena Tarnavsky of TAMSAT and a detailed description of the disaggregation methods can be found in Tanasky et al., (2014).

For all the calculations and experiments that will be done in the rest of this report, an assumption is made that rainfall from the manned synoptic weather stations at Tamale and Navrongo represent the truth. This assumption may not be entirely true due to the fact that several errors can occur in the collection, coding and transmission of data from manned weather stations.

2.4 Methods

2.4.1 Period of Year used for Analysis

Studies have shown that the growing season for Tamale and Navrongo lasts from April to August (AMJJA) (eg Antwi-Agyei et al., 2012, Kasei and Afuakwa 1991; Nkrumah et al., 2014). Therefore daily soil moisture availability factor, beta, for the period April to August was obtained for each of the 14 years between 1998 and 2011 for Tamale. This corresponds to 153 daily β values. The average of these beta values for the AMJJA period was then calculated using the following formula

\[ \beta_{avg} = \frac{1}{N} \sum_{i=1}^{N} \beta_{daily} \]  \hspace{1cm} eq4

Where \( \beta_{avg} \) is the average AMJJA beta, \( N \) is the number of daily beta values for the AMJJA period, \( i = 1,2,\ldots,N \) and \( \beta_{daily} \) is the daily soil moisture availability factor values.

Similarly for the experiments involving precipitation the average AMJJA precipitation is used and defined as follows;

\[ P_{avg} = \frac{1}{N} \sum_{i=1}^{N} P_{daily} \]  \hspace{1cm} eq5

Where \( P_{avg} \) is the average AMJJA precipitation, \( N \) is the number of daily precipitation values for the AMJJA period, \( i = 1,2,\ldots,N \) and \( P_{daily} \) is the daily precipitation values.
2.4.2 Standard Precipitation Index SPI Calculations

Calculation of the Standardized Precipitation Index, SPI for Tamale using both in-situ rainfall data (OBS) and satellite estimated rainfall data (TAMSAT) is done using the latest SPI software (SPI_SL_6.exe) which is available online at http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx.

To obtain good results, at least 20-30 years of monthly rainfall values is needed (WMO No.1090, 2012), while 50-60 years data is considered optimal and therefore preferable (Guttman, 1994). Fourteen years of monthly rainfall is used to calculate the SPI values for AMJJA. This gives a 5-month SPI which compares the precipitation for that period (AMJJA) with the same 5 month period over the historical record. The results obtained will then be compared to those obtained for SMDI using the methods described above.

2.4.3 Definition of Drought

The 25th percentile of the mean AMJJA beta was calculated when using the Original (O) soil and vegetation parameters in JULES configuration and forced with the data for all the 14 years. For the purpose of this study, JULES was setup to calculate the mean AMJJA beta of all the individual years and then to rank the years in order of increasing beta values. The 25th percentile value of beta for all 14 years is then considered the Drought Line and any year which has a value for beta or rainfall below this drought line is considered a drought year. Statistically, the 25th percentile is the lower quartile of a distribution of values. For any set of ordered numbers, the median divides the numbers into two halves. The upper half will be made up the highest values- in the case of this study, the highest beta values. The lower half will be made up of the lowest beta values. The lower quartile (25th percentile) further divides this lower half of beta values into two. Values of beta below the 25th percentile will therefore be among the lowest. For all drought analysis related to OBS data, the drought line is obtained from the 25th percentile when using the Original soil configurations when running the model with OBS data. The same holds true for runs done with TAMSAT data.
2.4.4 Definition of Wettest/ Driest Year

Meteorological Wettest Year (Wettest Year) is defined as the year in the time series with the highest total rainfall (precipitation) amount while Meteorological Driest Year (Driest Year) is the year in the time series with the lowest total rainfall (precipitation) amount. Agricultural Wet and Dry years are defined as the year with the highest and lowest soil moisture (or beta) respectively.

OBS as used in the rest of this report refers to calculations, experiments or plots made using in-situ weather data from the Tamale or Navrongo synoptic weather stations. On the other hand, TAMSAT is used to refer to calculations, experiments or plots based on satellite estimated rainfall. So OBS Wettest Year is therefore the year in the observation data that had the highest rainfall total. Similarly, TAMSAT Driest Year will mean the year in TAMSAT data that had the lowest rainfall total.

2.4.5 Statistical Methods

Pearson product-moment coefficient on linear correlation is used to quantify the relationship between variables used in the analysis. The formula for Pearson’s correlation coefficient is as follows;

\[ r_{X,Y} = \frac{\text{cov}(X,Y)}{\sigma_X \sigma_Y} \]

where \( r_{X,Y} \) is the pearson product-moment coefficient of linear correlation between two variables \( X \) and \( Y \), \( \text{cov}(X,Y) \) is the covariance between variables \( X \) and \( Y \) and \( \sigma_X \) and \( \sigma_Y \) are the standard deviations of variables \( X \) and \( Y \). The main advantage of using this Pearson product-moment coefficient of linear correlation is that in its squared form, as a coefficient of determination, that is \( r^2 \), it indicates the amount of variance in the predicted variable \( Y \) that is accounted for by the variation in the predictor variable \( X \). For our analysis \( X,Y \) could any two variables that are being compared. Hence \( X \) and \( Y \) could be rainfall and beta, OBS rainfall and TAMSAT rainfall etc.

To test the significance of the correlation coefficients obtained, we calculate p-values at 95% confidence interval. We use a significance level of 5% throughout the rest of this report. This means that for all the analysis done in this study, the computed \( r^2 \)-squared values are only
considered to be statistically significant at 5% level of significance or p-value less than 0.05. If p-value is greater than 0.05, then the correlation is considered insignificant.

Bias analysis between TAMSAT and OBS was done to find out whether TAMSAT was overestimating or underestimating variables. Bias is defined as;

$$Bias = \frac{1}{N} \sum_{all i} (TAMSAT_i - OBS_i) \quad eq7$$

Where N is the number of pairs of records, and i = 1,2,........N. TAMSAT$_i$ is the i$^{th}$ TAMSAT value and OBS$_i$ is the i$^{th}$ OBS value.

Bias calculated this way will give a measure of how higher or lower TAMSAT estimates are compared to OBS. A Bias value of zero would mean that TAMSAT Estimates perfectly match the values in OBS. Negative values will indicate that TAMSAT is underestimating while positive values show that TAMSAT is overestimating. The closer the bias value is to zero the better.
Chapter Three: Rainfall Patterns at Tamale and Navrongo

3.1 Introduction

This is the first part of the results and looks at the patterns of rainfall for Tamale and Navrongo using data from both in-situ synoptic weather observations (OBS) and satellite estimated rainfall data (TAMSAT). The main idea in this chapter is to compare TAMSAT rainfall data and OBS rainfall data. This is because the decision whether or not to use satellite estimated rainfall data in drought monitoring rests on how well the satellite estimated rainfall matches observed rainfall.

The chapter is in two main parts. The first part is about the meteorological seasons at Tamale and Navrongo and how well TAMSAT is able to show the seasons in comparison to OBS. The second part deals with annual rainfall and how this varies from year to year in both TAMSAT and OBS.

For rain-fed agriculture, which is the main focus of this study, the rainy season(s) is very vital for planning. All farm activities, from land preparation through planting to harvesting are planned to coincide with the rainy season. The onset and cessation of the rainfall seasons is therefore the focus in section 3.2. Section 3.3 looks at the annual total rainfall from 1970-2011 for Navrongo and Tamale and how this has varied over the years. Section 3.4 is where a detailed comparison of TAMSAT rainfall estimates and OBS rainfall is done. Finally, the chapter ends with an analysis of cumulative rainfall plots for Tamale and Navrongo.
3.2 Monthly Rainfall and Seasons

Figure 3.1 A and 3.1B; Mean monthly rainfall plots for Tamale and Navrongo respectively using OBS data.

Figure 3.1 C and 3.1D; Mean monthly rainfall plots for Tamale and Navrongo respectively using TAMSAT data.
Figures 3.1a to 3.1d shows the distribution of rainfall over Tamale and Navrongo for the various months of the year. There are two distinct seasons that can be seen from the graphs. In both Tamale and Navrongo, there is a unimodal rainy season followed by dry season. This is in contrast to southern Ghana that has a bi-modal rainy season and one dry season (Yengoh et al., 2010; Nkrumah et al., 2014).

For both OBS and TAMSAT the rainy season for Tamale starts in late April or early May. For OBS, the rainy season peaks in September while the peak of the TAMSAT rainfall is in August. The period between November and February each year is very dry. October is the transition from wet to dry seasons while March serves as the transition period between the dry and rainy seasons. The wettest and driest months of the year for Tamale from OBS were September and January respectively with 216.6mm and 3.5mm of rainfall while the wettest driest month for Tamale according to TAMSAT was August and December with 164.8mm and 1.5mm of rainfall respectively.

Navrongo shows similar patterns of rainfall to that of Tamale. Just like Tamale, there is a unimodal rainy season in both OBS and TAMSAT data followed by a dry season. Navrongo’s rainy season starts in April, peaks in August and ends in October. Unlike Tamale however, there is a gradual transition between rainy season and dry season for Navrongo. This transition period lasts for two months from September to October. November to February is the dry season at Navrongo. August and January are the wettest and driest months respectively for Navrongo according to both OBS and TAMSAT. OBS has a high rainfall of 262.7mm for August and a low of 0.5mm for January. For TAMSAT, August has 180.3mm of rainfall while January has a low rainfall amount of 0.1mm.

In general, TAMSAT is drier than OBS data; the dry season in TAMSAT is much drier than the corresponding dry season in OBS while the rainy season is not as wet as the corresponding rainy season in OBS. For both stations, TAMSAT rainy season starts in April and ends in August. OBS shows similar results in terms of start and end of the season for Tamale but differs in the end of the season for Navrongo.
3.3 Annual Rainfall

Figure 3.2a and 3.2b: Time series of annual precipitation for Tamale and Navrongo respectively for the period 1970-2011.

Figure 3.2a shows the time series of annual total rainfall at Tamale. The first observation from this figure is that from 1970 to 1997 the total rainfall did not show any variability as would be expected of annual rainfall totals. This observation prompted further investigation and it was realized that the rainfall totals from Tamale for that period (1970-1997) was just the climatological mean. Therefore, the data for this period could not be used for any further work.

Figures 3.2a and 3.2b show a lot of inter-annual variability in the rainfall for both Tamale and Navrongo. Even though the two stations are within the same agro-ecological zone as described in section 1.6 of chapter one, there are some differences in the year to year variations in the rainfall amounts over the two stations. 2004 was the wettest year at Tamale and 2011 was the driest year at Tamale. The wettest year for Navrongo was 1999 and the driest year was 1977.

The years before 1995 mostly had average or below average rainfall while the period after 1995 had average to above average rainfall. However, as shown by the trendline on both figure 3.2a and 3.2b, there has not been any significant change (p>0.05) in the total annual rainfall for either Tamale or Navrongo.
3.4 OBS rainfall and TAMSAT rainfall

In section 2.3.2, the dataset available for TAMSAT was described as being available only from 1983 to the present. In section 3.2 it was also shown that part of the rainfall data for Tamale (1970-1997) could not be used for further analysis because it was made of climatology mean values. In order to be able to compare TAMSAT and OBS data, we will limit the period used for the analysis relating to Tamale to 1998-2011 because there is rainfall data for both OBS and TAMSAT for this period. For Navrongo, there were no problems with the observation data but because TAMSAT only started from 1983, the analysis will be limited to the period between 1983 and 2011 when there is data from both TAMSAT and OBS. OBS data for the years after 2011 were not available for either Tamale or Navrongo even though TAMSAT has data for the years after 2011. This explains the fact that the analysis in the rest of this chapter and the study will be up to 2011.

![Figure 3.3a](image-url)

**Figure 3.3a:** Time series of annual precipitation for Tamale (1998-2011) using both OBS data and TAMSAT data. Red lines are for OBS while blue lines are for TAMSAT.
Figure 3.3b: Time series of annual precipitation for Navrongo (1983-2011) both OBS data and TAMSAT data. Red lines are for OBS while blue lines are for TAMSAT.

Figure 3.3c: Scatter plot of TAMSAT precipitation Vs OBS precipitation for the AMJJA period.

From figure 3.3a and 3.3b, it can be seen that TAMSAT underestimates the total rainfall for both Tamale and Navrongo. However, TAMSAT does well at showing the inter-annual variations in rainfall at both locations – years with increasing rainfall in TAMSAT correspond with years with
increasing rainfall in OBS (example is 1999 for both Tamale and Navrongo) and years with decreasing rainfall in OBS correspond with years with decreasing rainfall in TAMSAT (example is 1998 for Navrongo and 2001 for Tamale). The mean rainfall for Tamale between the period 1998 and 2011 was 1127mm and 837mm for OBS and TAMSAT respectively. The bias between the two rainfall measurements was -20.7. For Navrongo the mean 1983-2011 rainfall was 988 mm and 679mm for OBS and TAMSAT respectively and a bias of -10.6 between OBS and TAMSAT was recorded. TAMSAT therefore underestimates rainfall by 26 percent and 31 percent for Tamale and Navrongo respectively. The scatter diagram (figure 3.3c) also shows a very low correlation between TAMSAT rainfall estimates and OBS rainfall with an r-squared value of 0.24 and P>0.05 (P=0.07).

In order to find out the impact that this underestimation of rainfall will have on the ability of TAMSAT to match the soil moisture outputs from OBS, the annual time series of beta for both Tamale and Navrongo were also plotted and this is shown in Figures 3.3d and 3.3e.

When the variable is changed from rainfall to beta, the bias between OBS beta and TAMSAT beta reduces to -0.10 for Tamale while that for Navrongo reduces to -0.006.
Figure 3.3d and 3.3e: Time series of annual beta for Tamale (1998-2011) and Navrongo (1983-2011) respectively using both OBS data and TAMSAT data. Red lines are for OBS while blue lines are for TAMSAT.

Figure 3.3f: Time series of daily precipitation for all the 14 years using OBS. Blue lines are for the wettest year, brown lines are for driest years and the grey lines are the other years.
Figure 3.3g: Time series of daily precipitation for all the 14 years using TAMSAT. Blue lines are for the wettest year, brown lines are for driest years and the grey lines are the other years.

Figure 3.3f and 3.3g show the daily precipitation time series for Tamale using OBS and TAMSAT respectively. It was observed that the daily rainfall values from TAMSAT are considerably lower with a mean daily precipitation value of 2.3mm-day$^{-1}$ compared to that of OBS which has a mean daily precipitation value of 4.1mm. This means that TAMSAT underestimates the intensity of rainfall events at Tamale. Additionally, TAMSAT does not show any extreme rainfall events unlike OBS where some days record more than 100mm of rainfall. However, the seasonal cycle of rainfall that begins in about day 100 is very similar for both TAMSAT and OBS datasets. The occurrence of rainfall during the rainy season is also very well replicated by TAMSAT. What this means is that TAMSAT needs to improve the estimation methods in order to better capture the intensity of rainfall events.
3.5 Cumulative Rainfall Analysis

**Figure 3.4a and 3.4b:** Cumulative Rainfall graphs for Tamale and Navrongo respectively.

The rainfall at Tamale has a wider spread between the wettest year and the driest year than Navrongo indicating that rainfall at Tamale has higher inter-annual variability in rainfall than that of Navrongo. While the difference between the wettest and driest years for Tamale is about 900mm, that for Navrongo is just about 720mm.

For Navrongo, the wettest year (1999) had below average rainfall until the middle of the rainy season in June when rainfall amounts suddenly increased leading to that year becoming the wettest. The cumulative rainfall graphs show that there is more intra-seasonal variability in rainfall at Navrongo than there is at Tamale.

From figure 3.4a, Tamale has a mean annual rainfall is approximately of 1084mm. As indicated by the red solid lines, 850mm of rainfall at Tamale occurs between April and September which is approximately 78% of the annual mean rainfall. Navrongo has an average annual rainfall of 992mm, out of which 860 mm or 87% occurs between April and September. The results from these graphs show that Navrongo has lower mean annual rainfall than Tamale which is linked to the movement of the ITCZ as discussed in the introduction. From figure 3.3a the mean annual
rainfall for Tamale between 1998 and 2011 was 1127mm while the mean from 1970-2011 was 1084mm as shown in the cumulative plot. This suggests that for Tamale, the period between 1998 and 2011 has been wetter than the long term mean. For Navrongo, figure 3.3b shows that the mean 1983-2011 rainfall was 988mm while the cumulative rainfall plots show the mean 1970-2011 rainfall to be 992mm. This indicates that for Navrongo, there has been a decrease in rainfall of about 4mm relative to the long term mean. However, these changes in precipitation are not significant because of the high p-values (p>0.05) between them and rainfall.

The results from the cumulative plots shows that the period between April and September has the highest rainfall and is therefore the most important period for rain-fed agriculture.
Chapter Four: Results from JULES Experiments

4.1 Introduction

This is the second part of the results and focuses mainly on soil moisture. The first section of this chapter looks the soil moisture characteristics throughout the year. The response of soil moisture to precipitation at the beginning of the rainfall season as well as how the soil moisture changes in response to the cessation of the rainfall season is covered in this section. Additionally, the impact of long dry spells or extreme rainfall events on soil moisture will be explored in section 4.2.

Section 4.3 looks at the annual soil moisture and compares meteorological wet and dry years to agricultural wet and dry years. Whether or not a meteorological wet/dry year corresponds to a wet/dry agricultural year will be investigated here. If wet and dry meteorological years correspond to wet and dry agricultural years then rainfall deficits alone will be enough for drought analysis. If on the hand, there is a mismatch, that will mean other factors need to be considered.

Crops differ in the way they utilise soil moisture. While some are very efficient at utilising soil moisture for photosynthesis, others are inefficient users of soil moisture. By using C4 grass and C3 grasses as proxies for different vegetation types and running JULES with them, the changes in soil moisture can be seen and the potential impact of different vegetation cover on droughts can be inferred. This is covered in section 4. The infiltration and runoff properties are different for soil types depending on the clay, silt and sand contents of the soil. Additionally, different soil types will show differences in their water holding capacities. These properties of different soil type’s means that the soil moisture characteristics of different soils will be expected to differ. This concept is tested section 4.5 by using four different soil configurations and running JULES with each soil. The results could inform how irrigation resources are used in drought situations.

An assessment of drought which is based on soil moisture is done by comparing the results to standardized precipitation index in section 4.7 to see where there are any similarities and the differences that exist between them. For easy visualisation of the results and description done in this chapter, tables are provided that summarizes all the results at the end of the chapter.
4.2 Seasonal Soil Moisture Output

In order to understand how changes in precipitation affects changes in soil moisture throughout the season, one year’s (1999) output of soil moisture is compared to the precipitation. This is done for both OBS and TAMSAT using the same year (1999). By so doing the effect of extreme precipitation events and the effects of dry spells can be analysed. It is important to do this kind of analysis because extreme precipitation events lead to water logging while dry-spells can lead to loss of soil moisture and crop failure. Both events constitute a risk to agriculture.

Figure 4.1a and 4.1b: Graph showing the seasonal changes in total soil moisture in response to changes in precipitation for a selected year at Tamale using OBS and TAMSAT respectively.
Figure 4.1a and 4.2b shows the changes in total soil moisture in response to changes in precipitation throughout a selected year for OBS and TAMSAT respectively. Apart from the fact that TAMSAT underestimates the rainfall intensity and hence the total soil moisture, there is a lot of similarities in both graphs. In both plots, the year starts with relatively high soil moisture compared with other parts of the season. For both datasets, the soil moisture drops to its lowest point between April and May even though this is the start of the raining season from figure 3.1a and 3.1c. As discussed in section 3.2 and shown in figures 3.1a and 3.1c, the rainy season starts in April and ends in September. However, it is not until June that the soil moisture starts to increase appreciably and peaks in October/November. This shows a lag of about 2 months between the onset of the rainy season and an appreciable increase in total soil moisture.

Similarly, there is a lag between the cessation of the rainy season and a drop in the soil moisture. When the harmattan or dry season starts in November and the rainy season ends, the total soil moisture begins to drop also. From figure 3.1a, January was the driest month for Tamale but as figures 4.1a and 4.2b shows, April has the lowest total soil moisture. This means that the lowest precipitation and the lowest levels of soil moisture are about 3 months apart.

Intra-seasonal changes in precipitation also affect the total soil moisture in the soil. Examples of these intra-seasonal changes have been circled on figures 4.1a and 4.1b. Large changes in precipitation can lead to immediate corresponding increase in the total soil moisture as shown in green circles on both figure 4.1a and 4.2b. Such increases in soil moisture over a short period of time can lead to water logging and leaching of soil moisture away from roots of plants. Periods of dry spells are shown with yellow circles on figure 4.1a and 4.2b. Unlike extreme rainfall events, dry spells do not have immediate impact on the soil moisture. There must be a few days of no rainfall for it to have an effect on the total soil moisture content of the soil. The period needed for this lack of rainfall to impact negatively on soil moisture is estimated at about one week. Dry spells mean that the soil moisture is not being recharged while at the same time evapotranspiration is taking place. This can lead to depletion of soil moisture and cause wilting in crops.
4.3 Annual Total and Top Level Soil Moisture Output

Figure 4.2a: Time series of daily total soil moisture for Tamale for each individual year using OBS. Wettest meteorological year is shown in blue, the driest meteorological year is shown in brown and the remaining years are shown in grey. The mean total soil moisture for all the years is 790kgm$^{-2}$, the mean for the wettest year is 895kgm$^{-2}$ and the mean for the driest year is 778kgm$^{-2}$.

Figure 4.2b: Time series of daily total soil moisture for Tamale for each individual year using TAMSAT. Wettest meteorological year is shown in blue, the driest meteorological year is shown in brown and the remaining years are shown in grey. The mean total soil moisture for all the years is 356kgm$^{-2}$, the mean for the wettest year is 448kgm$^{-2}$ and the mean for the driest year is 355kgm$^{-2}$.
Figure 4.2c: time series of daily top level (0.1m) soil moisture for Tamale for each individual year using OBS. Wettest meteorological year is shown in blue, the driest meteorological year is shown in brown and the remaining years are shown in grey. The mean soil moisture at 0.1m level for all the years is 20kgm$^{-2}$, the mean for the wettest year is 23kgm$^{-2}$ and the mean for the driest year is 20kgm$^{-2}$.

Figure 4.2d: time series of daily top level (0.1m) soil moisture for Tamale for each individual year using TAMSAT. Wettest meteorological year is shown in blue, the driest meteorological year is shown in brown and the remaining years are shown in grey. The mean soil moisture at 0.1m level for all the years is 11kgm$^{-2}$, the mean for the wettest year is 14kgm$^{-2}$ and the mean for the driest year is 12kgm$^{-2}$.
Figure 4.2a and 4.2b show the time series of daily total soil moisture within all the four soil levels (depth of 3m) while 4.2c and 4.2d show the daily soil moisture at a depth of 0.1m (10cm). The wettest years in terms of total annual rainfall are shown in blue while the driest rainfall years are shown in brown. The remaining 12 years are all shown in grey colour.

The wettest years in both OBS and TAMSAT had above average soil moisture but were not the years with the highest total moisture. This result is observed in both total soil moisture and top level soil moisture. The wettest meteorological year from OBS had a average total soil moisture of 859kgm$^{-2}$ which was higher than the mean of all the 14 years (790kgm$^{-2}$) but lower than that of wettest year in soil moisture terms which was 864kgm$^{-2}$. For TAMSAT, the wettest meteorological year had average soil moisture of 448kgm$^{-2}$ which was higher than the mean of all the years’ together (356kgm$^{-2}$) but lower than the 456kgm$^{-2}$ which was the highest recorded. This is confirmed by the fact that the blue lines which represent the wettest years in the rainfall time series for Tamale (from figure 3.3a, these are 2004 and 2009 for OBS and TAMSAT respectively) lie beneath some other years in figures 4.2a to 4.2d.

For OBS graph (figure 4.2a), the total soil moisture for the wettest year was actually lower than that for the driest year at the beginning of the year. The total soil moisture increased during the rainy season but even then it did not attain the highest soil moisture. Similar for TAMSAT (figure 4.2b), the wettest year in terms of rainfall was not the wettest in terms of soil moisture.

The average total soil moisture for Tamale according to OBS was 790kgm$^{-2}$ while that for the driest year was 778kgm$^{-2}$. The year with the lowest total soil moisture had 765kgm$^{-2}$. The result from TAMSAT shows mean total soil moisture of 356kgm$^{-2}$ and that for the driest year was 355kgm$^{-2}$ while the lowest soil moisture recorded was 350kgm$^{-2}$. These results show that the driest years in both TAMSAT and OBS were not the driest years in terms of total soil moisture even though their total soil moisture was below average throughout the year.

The results for top level soil moisture shown in figure 4.2c and 4.2d are very similar to that of the total soil moisture; the wettest years in both TAMSAT and OBS did not have the highest top level soil moisture and the driest years did not have the lowest top level soil moisture. The wettest meteorological year from OBS had average top level soil moisture of 23kgm$^{-2}$ which was
higher than the average of all the 14 years together (20kgm⁻²) but lower than the highest recorded which was 25kgm⁻². TAMSAT’s wettest meteorological year had an average of 14kgm⁻² top level soil moisture which was lower than the highest recorded (17kgm⁻²) but higher than the 11kgm⁻² which was the average top level soil moisture for all the 14 years. The driest meteorological years did not have the lowest top level soil moisture. In the case of OBS (figure 4.2c), the driest year actually had above average top level soil moisture at the beginning of the year. For TAMSAT, the driest meteorological year had an average of 12 kgm⁻² top level soil moisture which was higher than both the lowest recorded (10kgm⁻²) and average top level soil moisture for all the 14 years which was 11kgm⁻². The driest meteorological year in OBS had an average of 20kgm⁻² which was the same as the mean and higher the lowest recorded (17kgm⁻²).

In general, there is a lot of variability in both the total soil moisture and the top level soil moisture from year to year. Variability also exists on daily and seasonal basis. OBS soil moisture shows more variability than TAMSAT soil moisture and top level soil moisture is also more variable than total soil moisture. TAMSAT has lower total and top level soil moisture compared to OBS.

In both OBS and TAMSAT, the total and top level soil moisture follow the seasonal cycle of rainfall discussed in section 3.1 of chapter 3. There are differences between how the top level soil moisture and the total soil moisture respond to the changes in seasons. Top level soil moisture rises sharply from day 90 (March 31st) which is the transition period between dry and rainy seasons at Tamale (from figure 3.1a and3.1c). The top level soil moisture keeps rising until it peaks between day 200 and day 300 (July 19 and October 28). The increase in total soil moisture is more gradual than that of top level soil moisture. Total soil moisture starts to rise after day 100 (April 10) and peaks between day 250 and day 300 (September 7 and October 28). Hence, there is a lag of about 2 months and 4 months between the onset of the rainy season and the peak in top level soil moisture and total soil moisture respectively. Once the rainy season stops, top level soil moisture drops steeply while the drop in total soil moisture is more gradual. Overall, top level soil moisture responds to changes in precipitation more rapidly than total soil moisture.
These results show that a meteorological wet year is not necessarily an agricultural wet year and a meteorological dry year is also not necessarily an agricultural dry year. It also means that soil moisture is not solely governed by precipitation. This is the rationale behind the decision to use soil moisture rather than rainfall for drought analysis. The use of a land surface model also allows for the incorporation of other variables in drought assessment that traditional drought indices fail to take into account. Theoretically, this should lead to improvement in the assessment of droughts. The sections that follow will therefore define droughts in terms of soil moisture (beta) and test how these changes in response to changes in vegetation cover and changes in soil types.

4.4 Effect of vegetation cover on Soil Moisture

The effects of changes in vegetative cover on the soil moisture that will be available to crops (beta) and agricultural droughts are explored in this section. By changing the percentage of the land surface that is covered with C3 and C4 crops, baresoil and broadleaf trees, an analysis of the corresponding changes in beta and whether or not droughts occur is done. The drought line used here is based on the 25th percentile of the mean April to August (AMJJA) beta as defined in section 2.4.3 of chapter 2. Beta values range from 0 to 1 and correspond to high/low water stress on plants respectively as described in section 2.2.4.

The effects of these different vegetation types on soil moisture will be seen in changes to the mean AMJJA beta as well as the number of years that fall below the drought line for each vegetation cover scenario. These scenarios are defined by the percentage of C3, C4, broadleaf trees and baresoil that are represented as listed in table 2.1. Two special cases of vegetation cover scenarios are used as proxies for mixed cropping which is a common practice in northern Ghana. These two are denoted as 50C4* and 50C3*.

The period between April and August has been chosen for drought assessment because it is the period where most farming activities take place. Using the entire year will be meaningless because little or no farming activities take place in the period between November and March when the dry season or harmattan occurs. September and October is usually the period for harvesting and any impact of drought will have already occurred.
Figure 4.3a: Time series of AMJJA Beta for Tamale using different C3 configurations and OBS data. These C3 configurations are 50C3*, 50C3, 75C3 and 100C3 respectively from top to bottom.

Figure 4.3b: Time series of AMJJA Beta for Tamale using different C3 configurations and TAMSAT data. These C3 configurations are 50C3*, 50C3, 75C3 and 100C3 respectively from top to bottom.
Figure 4.3c: Time series of AMJJA Beta for Tamale using different C4 configurations and OBS data. These C3 configurations are 50C4*, 50C4, 75C4 and 100C4 respectively from top to bottom.

Figure 4.3d: Time series of AMJJA Beta for Tamale using different C3 configurations and TAMSAT data. These C3 configurations are 50C4*, 50C4, 75C4 and 100C4 respectively from top to bottom.
The effects of different crop types on soil moisture availability and drought is shown figures 4.3a to 4.3d. From the figures, increasing the percentage of C3 crops on the land surface leads to a decrease in the mean value of beta just as increase the percentage of C4 crops leads to a decrease in beta. This is consistent in both OBS and TAMSAT. For TAMSAT, there are no drought years for any of the C3 configurations. The introduction of C3 grass on a land surface covered with C4 (50C4 and 50C4*) grass leads to a marginal increase in the value of beta. On the contrary, the introduction of C4 crops onto a land surface that has predominantly C3 grass leads to a decrease in the the mean beta values. Due to the fact that the value of beta decreases as the proportion of land surfaces covered with crops decrease, there are more drought years for scenarios involving 100C3 and 100C4 than there is for any other scenarios.

Comparatively, experiments done with TAMSAT produces fewer drought years than OBS even though the beta values are lower. This as a result of the definitions that were used for the drought line in both sets of experiments. While the drought line for OBS experiments was 0.63, that for TAMSAT was 0.52 and that explains why OBS has more drought years than TAMSAT. The introduction of C3 crops onto a land surface that is predominantly covered with C4 crops leads to an increase in soil moisture availability (beta). On the other hand, introducing C4 crops onto a land surface that is predominantly covered with C3 crops leads to a reduction in soil moisture availability factor (beta). This could be misinterpreted as meaning that C3 crops are more efficient at utilising soil moisture and hence will use less soil moisture resulting in fewer drought. However, C3 crops require more water than C4 crops. C4 grass on the other hand a very effective at using soil moisture for photosynthesis and this leads to a reduction in beta. By the definition of beta in section 2.2.4, it is a measure of the stress that plants will experience during photosynthesis as a result of lack of moisture. Therefore plants that utilise more soil moisture in photosynthesis will experience a stronger stress and therefore show more drought years. There is therefore a higher risk of agricultural drought occurring for surfaces covered with C4 crops than there is for surfaces with C3 crops.
4.5 Effects of different soil types on Soil Moisture

**Figure 4.4a:** Time series of AMJJA beta for Tamale using different soil types and OBS data. These are O, CL, SL and LS respectively from top to bottom together with their mean beta values.

**Figure 4.4b:** Time series of AMJJA beta for Tamale using different soil types and TAMSAT data. These are O, CL, SL and LS respectively from top to bottom together with their mean beta values.
Figure 4.4a and 4.4b shows the results of the experiments done using the four different soil types listed in chapter two, namely Original (O), Clay Loam (CL), Sandy Loam (SL) and Loamy Sand (LS). The figures show that there is clear year to year variability in the mean AMJJA beta values. There is also variability in beta from one soil to another. Soils with higher with clay contents have lower beta values and thus produce the highest number of drought years. CL which has the highest clay content of all the four soil types produces the most number of drought years (10 in OBS and 9 in TAMSAT) while LS which has the lowest clay content produces the least drought years (2 in OBS and none in TAMSAT). O and SL soils produce very similar results because they have similar compositions as shown in table 2.2 of chapter 2.

Even though TAMSAT has comparatively lower beta values, it produces similar results to that of OBS with some little variations between the two. In the OBS experiments, 2010 is not a drought for all soil types but in TAMSAT experiments 2010 is a drought year for all soil types except LS. Also, for all soil types, TAMSAT experiments do not show 2011 as a drought year but OBS experiments do.

4.6 Correlation Analysis

Correlation analysis from the description given in section 2.4.5 allows for the relationship between two variables to be quantified. The results described in this chapter and chapter 3 have been based on rainfall, soil moisture and beta. Rainfall is the main factor influencing the amount of moisture in the soil and by extension the value of beta. Through the use of the pearson product moment correlation coefficient and its associated p-values, it will be possible to tell if there is a strong or weak relationship between rainfall and beta and how significant that relationship is. That will be the focus of this section.
Figure 4.5a: Scatter plots of OBS AMJJA beta and OBS AMJJA precipitation for different soil types. O is in the top left corner, CL is in the right corner, SL is in the bottom left corner and LS is in the bottom right corner.

Figure 4.5b: Scatter plots of TAMSAT AMJJA beta and TAMSAT AMJJA precipitation for different soil types. O is in the top left corner, CL is in the right corner, SL is in the bottom left corner and LS is in the bottom right corner. Outlier point is circled in red.
Figure 4.5a and 4.5b show the correlation between AMJJA precipitation and AMJJA beta for OBS and TAMSAT respectively. The results show that CL soil has the highest correlation between precipitation and beta followed by LS soil. Additionally, figures 4.4a and 4.4b show that experiments done with CL soils produces more drought years than the other soils. In general OBS shows a stronger relationship between precipitation and beta than TAMSAT.

The r-squared values between AMJJA precipitation and beta for OBS ranged from approximately 0.37 and 0.42 indicating that between 37 percent and 42 percent of the variance between the two variables is explained by the linear fit. This relationship between OBS beta and OBS rainfall is statistically significant because the all the p-values are less than 0.05 (P-values range between 0.011 for CL and 0.019 for SL). For TAMSAT, the r-squared values between AMJJA precipitation and beta ranged between 0.08 and 0.12 indicating that only 8 to 12 percent of the observed variations in beta can be explained by changes in precipitation. These low correlation values are also backed up by p-values which are all greater than 0.05 indicating that there is no statistically significant relationship between TAMSAT beta values and TAMSAT rainfall.

There are a number of reasons that could explain the low correlation between rainfall and beta.

One explanation for the low correlation and high p-values is that there is a lag between beta and rainfall. As shown in figures 4.1a and 4.1b soil moisture lags rainfall by about 2 months. Even though the rainy season starts in April as shown in figure 3.1a, soil moisture is at its lowest levels in the same month of April and only starts to increase considerably in early June as shown on figures 4.1a and 4.1b. This lag period will mean that period of high rainfall will be out of phase with periods of high soil moisture and this could affect the correlation between the two variables.

Another possible explanation for the low correlation values between beta and rainfall is the presence of noise in the data. There are only fourteen data points and so it is easy for outliers such as those circled on figure 4.5a and 4.5b to have a big impact on the r-squared value and by extension the correlation. We therefore removed the outliers and calculated r-squared and p-value again (plots not shown). When the outliers are removed, TAMSAT has a higher r-squared values ranging from 0.52 to 0.67 compared with the r-squared values for OBS which range from
0.41 to 0.52. CL has the highest correlation between precipitation and beta followed by SL, O and LS has the lowest correlation between precipitation and beta. The results show that for TAMSAT between 52 and 67 percent of the observed variations in beta for the various soils can be explained by changes in precipitation. For OBS between 41 and 52 percent of the variations in beta for the soils can be explained by changes in precipitation. The p-value for all these correlation coefficients showed the relationship between beta and rainfall was significant (p<0.05) for all the cases.

Even if the new r-squared values were a ‘true’ representation of the relationship between soil moisture and rainfall, it will still not explain all the variations in beta. This is because the r-squared values show that up to 67 percent of the variations in beta are due to rainfall. That leaves 33 percent of the variations in beta unaccounted for. This means that other factors play a role in the amount of soil moisture that will be available for plant growth.

Figure 4.5c: Scatter plots of TAMSAT AMJJA beta and OBS AMJJA beta for different soil types. O is in the top left corner, CL is in the right corner, SL is in the bottom left corner and LS is in the bottom right corner.
Figure 4.5c shows the relationship between OBS beta and TAMSAT beta. The r-squared values obtained ranged from 0.44 for LS soil to 0.51 for CL soil. With p-values ranging from 0.004 to 0.009, this indicates a strong and statistically significant relationship between TAMSAT beta values and OBS beta values. In figure 3.3c when we calculated the correlation between TAMSAT rainfall and OBS rainfall, a low r-squared value of 0.24 and a p-value of 0.07 was obtained indicating that there was a weak relationship between OBS rainfall and TAMSAT rainfall. The improvement in the relationship between TAMSAT values and OBS values from rainfall to beta shows that even though TAMSAT underestimates the rainfall amount and intensities, the effect of this rainfall underestimation is minimised when the moisture available to plants is considered. Since OBS has a higher rainfall rate, its run-off rate will also be higher than that of TAMSAT. Most of the excess rainfall in OBS will therefore be unavailable to plants. TAMSAT’s low rainfall rate will also mean a lower run-off rate. The difference in run-off rate between OBS and TAMSAT could offset the difference in rainfall amount between TAMSAT and OBS and thereby lead to a stronger relationship between TAMSAT beta and OBS beta.

4.7 Comparison of drought assessment using beta and rainfall.

Figure 4.6a: Time series of AMJJA Beta for Tamale using OBS data (top) and TAMSAT data (bottom).
Figure 4.6b: Time series of AMJJA Rainfall for Tamale using OBS data (top) and TAMSAT data (bottom).

Figure 4.6c: Time series of AMJJA SPI for Tamale using OBS (top) and TAMSAT (bottom) data.
Figures 4.6a to 4.6c show time series of AMJJA beta, rainfall and SPI respectively for the period 1998-2011. The drought line in figure 4.6a and 4.6b is based on the definition of drought which is any year for which AMJJA beta or rainfall falls below the 25th percentile. The drought line and wetness line in figure 4.6c are based on SPI definitions as given by (McKee et al., 1993).

The results of the standardized precipitation index, SPI, calculations show that for the analysis done using OBS data, there were three drought years (1998, 2000 and 2001) and 2 wet years (1999, 2003). Of the three drought years one (1998) was in the category of extreme drought. The other two qualified as moderately dry years. The two wet years were both moderately wet with no extremely wet year recorded. The SPI calculations based on TAMSAT data shows four drought years (1998, 2001, 2007, 2010) and two wet years (2008, 2009). All the drought years were moderate with values ranging from -1.1 to -1.2. Of the two wet years, one (2008) was moderately wet while the other (2009) was very wet.

The analysis done with AMJJA rainfall and our definition of drought produces four and five drought years respectively when using OBS and TAMSAT data. For OBS the drought years were 1998, 2001, 2006 and 2011. The drought years according to TAMSAT data were 1998, 2001, 2005, 2006 and 2010. The drought analysis based on beta gives similar results to that of rainfall; there are four and five drought years when using OBS and TAMSAT data respectively. However, not all the drought years are the same as those found when the analysis was done with rainfall. The drought years based on beta in OBS are 2006, 2007, 2009 and 2011. TAMSAT drought years based on AMJJA beta are 2001, 2005, 2006, 2007 and 2010. There is more agreement between TAMSAT drought years based on AMJJA rainfall and AMJJA beta (4 years in common) than there is between OBS drought years based on those two parameters (2 years in common).

The drought and wet years obtained from the SPI corresponds well with the annual rainfall values as shown in figure 3.3a in Chapter 3. 2001 which was a drought year in the SPI calculations is shown in figure 3.3a to have less than average rainfall. Similarly, 2008 which is a wet year in TAMSAT SPI calculations has a high rainfall amount. However, the SPI fails to show 2004 and 2010 as wet years in the OBS calculations even though these two years had very high rainfall amounts as shown in figure 3.3a.
### Summary of Results

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**Table 4.1:** Summary table of all the drought and non-drought years obtained using AMJJA TAMSAT rainfall and beta, OBS rainfall and beta and SPI calculations based on TAMSAT and OBS data.

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**Table 4.2:** Summary table of all drought and non-drought years obtained for experiments involving different soil type O, CL, SL and LS. OBS and TAMSAT indicate that we use OBS or TAMSAT data respectively with the different soil types.
### Table 4.3: Summary table of all drought and non-drought years obtained for experiments involving different vegetative cover involving C3 grass. OBS and TAMSAT indicate that we use OBS or TAMSAT data respectively with the different soil types.

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### Table 4.4: Summary table of all drought and non-drought years obtained for experiments involving different vegetative cover involving C4 grass. OBS and TAMSAT indicate that we use OBS or TAMSAT data respectively with the different soil types.

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Tables 4.1 to 4.4 summarizes all the results obtained from the experiments conducted with vegetation (C3 and C4), soils (O, CL, SL and LS) and also the drought analysis based on AMJJA rainfall and beta as well as SPI for Tamale. Brown boxes represent drought years while blue boxes represent non-drought years. The tables can be interpreted as follows

- The rows represent model parameter configurations used in the experiments. For each configuration, there are two experiments, one for OBS and the other is for TAMSAT. That is why each of the names in the rows has either OBS or TAMSAT preceding them.

- The columns are the years that were used in the analysis. There are 14 years in total from 1998-2011.

- A brown box indicates a drought year based on a particular model configuration.

- A blue box indicates a non-drought year based on a particular model configuration.

As an example, in Table 4.2, OBS O represents experiments carried out with Original (O) soil configuration and using OBS data. For that experiment, there are brown boxes for 2006, 2007, 2009 and 2011 indicating that those four years were drought years. It can also be easily seen from the summary tables that 1999, 2003 and 2004 were not drought years under any of the vegetation or soil type configurations for both TAMSAT and OBS.

From the summary tables, it is also obvious that there is a lot of variability in the model’s output and characterisation of years as either drought years or non-drought years. Depending on a particular scenario, the model characterises a particular year as drought year at one point and then as a no drought year at another point. What these tables reveal as already discussed above is that different soil types and different vegetative cover has impact on the soil moisture and therefore the occurrence of agricultural drought.
Chapter Five: Discussion

5.1 Introduction

This work set out to assess agricultural risk in Africa. Our main focus was on drought and the impact it has on farming activities. The Joint UK Land and Environment Simulator Model (JULES), which is the land surface scheme of the UK Met Office Unified Model (UM) was used to simulate the changes in soil moisture to different forcing conditions.

Traditionally, drought indices and drought research have been based precipitation. By this traditional approach, drought indices such as Palmer drought Severity Index and Standardized Precipitation Index defined droughts in terms of precipitation deficits. Years with lower than average rainfall were considered drought years and the severity of droughts were related to severity of the precipitation deficits. Our view was that rainfall alone was not enough for assessing agricultural droughts because not all the rain that falls to the ground becomes available to plants for growth. We therefore used soil moisture availability factor, beta, which is a measure of the actual moisture that plants could access for their growth to define droughts. We further hypothesized that the value of beta could be affected by the type of soil and the vegetative cover on the soil.

This chapter is a summary of all the key findings of our study and its implications on decision making as far dealing with agricultural risks in general and droughts in particular are concerned. The chapter is divided into five thematic areas. First we take a look at the rainy season and compare it to the agricultural season. Our focus here is how changes in soil moisture throughout the year could impact on agricultural production. The next theme we discuss in this chapter is how good TAMSAT rainfall estimates are when compared to observations. This is an important aspect of this work because as stated in the introduction, there is a lack of data for many parts of Africa and therefore rainfall estimates from satellites such as TAMSAT data could be very useful in drought planning. The relationship between meteorological drought and agricultural droughts are then discussed in section 5.4 based on soil moisture characteristics of meteorologically wet and dry years. We mainly stress the challenges with using rainfall as the sole indicator of
droughts. The last two themes explored in this chapter provide answers to how vegetation and soil types affect soil moisture and in turn agricultural drought.

5.2 Rainfall Season and agricultural season

Our results show there is a unimodal rainy season that starts in April and peaks in August for Tamale and September for Navrongo. This is consistent with other findings (see Amekudzi et al., 2015, Nkrumah et al., 2014 and Antwi-Agyei et al., 2006). For example Amekudzi et al., (2015) put the onset of the rainy season for Tamale between the third dekad of April and the first dekad of May. The farmers in this area being cognizant of this rainfall season plan their farming activities to coincide with the rainy season. Preparation of land begins in March in readiness for the rainy season (Antwi-Agyei et al., 2012). Farmers usually plant their crops when the rainy season starts.

The rainy and dry seasons described in chapter 3 affect the total soil moisture in the soil and the top level soil moisture as well. There is a lag of about 2 months between the start of the rainy season and any appreciable increase in the total soil moisture. A similar study by Jamali et al., (2011) found that for Sub-Saharan Africa, soil moisture at depths of up to 1 meter lagged precipitation by a period of between 24 and 32 days. There is a longer lag time between total soil moisture and precipitation in our study is than the findings of Jamali et al., (2011) because while they considered depths of up to 1 meter, we are using depths of up to 3 meters.

There is no lag time between the onset of the rainy season and appreciable increase in the top level soil moisture. However the top level soil moisture is only for the topmost 10 centimeters of the soil. Most of the crops grown in the study area have roots that only go to shallow depths of up to 50 centimeters (Jamali et al., 2011) but depending on the soil, vegetation and nutrients characteristics of the soil, the roots can reach depths up to 1 meter (Kurc and Small, 2007).

Plants grown at the beginning of the rainy season in April will have enough soil moisture to support them at germination and during the early stages of growth. But as they mature and develop deeper roots, there will not be enough moisture to support them as the total soil moisture is at its lowest in April and May. The risk of crop failure is therefore high for farmers who plant
in April. An ideal time to start planting will be late May or early June when there is enough top level soil moisture to support germination and early stages of plant growth as well enough total soil moisture in the soil layers to support the plants as they develop deeper roots during maturation. However, since there is a lot of intra-seasonal variability in both top level and total soil moisture, it will be necessary to monitor the soil moisture throughout the year and irrigate when soil moisture levels begin to fall.

5.3 Comparison between observed (OBS) data and TAMSAT data

From the analysis of seasonal and annual rainfall, it was observed that TAMSAT consistently underestimates the intensity and total rainfall for Tamale and Navrongo when compared to observations but the occurrence of rainfall during the rainy season. The average rainfall annual for Tamale from observations was 1127mm while that for TAMSAT was 837mm meaning that TAMSAT underestimates the annual rainfall by approximately 25%. TAMSAT however matches the observations well in the replicating the inter-annual variability in the rainfall. The rainy and dry seasons in TAMSAT are the same as those in observations even though the amount of rainfall and its intensity during the rainy season is less in TAMSAT than in observations. Similar results have been obtained by Maidment et al., (2014) who compared TAMSAT datasets to rainguage data and over Africa found that TAMSAT underestimates the Africa-wide mean annual rainfall by 21%. Asadullah et al., (2008) and Thorne et al., (2001) also found that TAMSAT underestimates high rainfall events over Ethiopia and Southern Africa respectively.

The correlation between TAMSAT rainfall and OBS rainfall for the AMJJA period was 0.24 with p>0.05 which meant a weak and insignificant relationship between OBS rainfall and TAMSAT rainfall. The r-squared value between TAMSAT beta and OBS beta was 0.51 at p<0.05 indicating a strong and significant relationship between TAMSAT beta and OBS beta. Surface and sub-surface run-off could be the main reason for the change in relationship between TAMSAT rainfall/beta and OBS rainfall/beta. As discussed in the model description setion 2.2.1, once the soil becomes saturated, JULES adds any excess rainfall to the runoff. According to Mithen and Black (2011) more intense rainfall leads to increased runoff. OBS which had more intense rainfall and higher rainfall amount will also have more run-off than TAMSAT which had
less intense rainfall. The fraction of OBS rainfall that becomes unavailable to plants will therefore be greater than the fraction of TAMSAT rainfall that becomes unavailable to plants. What this means is that even though TAMSAT underestimates rainfall over Africa, it can still very useful for agricultural drought assessment because the rainfall that satellites fail to capture may not become available to plants in the long run. As satellite technology improves, our ability to estimate rainfall using satellites is also likely to improve. The use of satellite estimated rainfall for drought analysis therefore has great prospect even though there is the need to improve upon the methods of satellite rainfall estimation.

5.4 Relating Meteorological drought to agricultural drought

The results from daily top level soil moisture and total soil moisture plots indicated that the wettest meteorological years were not the wettest in soil moisture terms and the driest meteorological years did not record the highest soil moisture deficits. The soil moisture also showed a lot of variability throughout the year. What this means is that it is possible to have a year with very high total rainfall and yet that year will not have enough soil moisture. Meteorological wet years do not necessarily correspond to agricultural wet years neither do meteorological dry years correspond to agricultural dry years. Drought indices that are based on precipitation alone may therefore have limited application for agricultural purposes. When our assessment of drought was based on AMJJA rainfall alone, it largely agreed with that of the Standardized Precipitation Index, SPI, which is also based entirely on rainfall. When we based our drought assessment on AMJJA soil moisture available to plants instead, the results were different from that of the SPI. This basically shows that a meteorological drought year does not necessarily correspond to agricultural drought year.

The soil moisture characteristics in any particular year will be affected by the soil moisture of the years immediately preceding it. This is what we have referred to as antecedent moisture which is the soil moisture condition prior to the onset of the rainy season. Wei and Nearing, (2011) showed that the previous soil moisture conditions of the soil will affect the runoff rate and the infiltration rate at the surface. It follows that if the preceding year had below average soil moisture, then there will be a soil moisture deficit which must be filled first before any appreciable increase in soil moisture can occur. This implies that even though a year may have a
lot of rainfall, most of the rainfall will be used to reduce the soil moisture deficit inherited from the previous year and the year may end up not being an agriculturally wet year. Our results from figure 4.1a and 4.1b showed that the wettest meteorological year in both TAMSAT and OBS started with very low soil moisture which contributed to them not being the wettest agricultural years. In other words they had low antecedent soil moisture. On the other hand, the driest meteorological years had above average antecedent moisture from the beginning which prevented them from becoming the driest agricultural years.

It is very important then to take the soil moisture characteristics of the years immediately preceding the year of interest into account in determining whether there will be excess or shortage of soil moisture. This is not done in generating traditional drought indices SPI and PDSI. As described in chapter one, these indices are mainly based on precipitation and the calculations are done based on long term (at least 30 years) mean rainfall for a particular location. However the long term mean rainfall does not have any impact on the rainfall of any particular year and thus does not also have any impact on the soil moisture of any particular year. What does have impact on the soil moisture of any year is the rainfall and soil moisture characteristics of the years (one to two years) immediately preceding that year. Together with the rainfall for the year of interest and factors such as evapotranspiration, this will determine the soil moisture available to plants.

From the experiments using both OBS and TAMSAT data, it was observed that between 41 and 52 percent of the variability in the soil moisture available to plants could be explained by changes in rainfall. That means about 50% of the variation in soil moisture available to plants is due to some factors other than rainfall. These factors include evapotranspiration, the rainfall rate, the infiltration rate, temperature, vegetation cover and type, soil type among others. In modelling beta, JULES takes the soil moisture and rainfall characteristics of the previous year into consideration and adjusts the soil moisture at the start of any particular year to match that of the preceding year. The findings of Ntale and Gan (2003), and NCAR (2015) indicate that the inclusion of the factors listed above in Standardized Precipitation Index and Palmer Drought Index calculations leads to better results. Since JULES took all these factors into consideration in modelling beta, it stands to reason that drought indices based on beta will be much more suited to
agriculture than traditional drought indices. These results highlight the need to consider other factors in the assessment of agricultural drought other than rainfall. It also shows the potential usefulness of relying on soil moisture availability factor, beta, for assessing agricultural droughts.

5.5 Effect of vegetation and soil types on agricultural drought

The results was obtained in section 4.4 (figures 4.3a, 4.3b, 4.3c and 4.3d) showed that when the when C3 crops were on the land surface, the AMJJA mean beta increased compared to when the land surface was covered with C4 crops. There were less drought years in all the experiments when C3 grass was used as the dormant vegetation type than when C4 grass was used. Indeed but for 2011 when there was drought with a 100 percent of the land surface covered with C3 crops , there was no other drought year when using any of the C3 crop configurations. One way to explain this is that C3 crops are more efficient at utilising soil moisture than C4 crops are. However, this explanation is inconsistent with other research findings. Sinclair et al., (1984) and Condon et al., (2002) have both shown that C3 crops are less efficient at utilising soil moisture for photosynthesis. By definition of beta in section 2.2.4, it is a measure of the soil moisture stress on photosynthesis and so the other way to interpret this result is that because C3 crops are less efficient at utilising soil moisture for photosynthesis, most of the soil moisture available to them will be unused leading to less droughts being recorded by the model. In other words, the model is recording less soil moisture stress on photosynthesis for C3 crops than for C4 crops.

The experiments done with a mixture of C3 and C4 (50C4* and 50C3* vegetation scenarios) grasses indicate that mixed cropping could be used as a way of dealing with soil moisture deficits.

Different soils respond differently to incident rainfall which in turn affects the amount of soil moisture that is available to plants. The sensitivity of soil moisture to soil type is made very evident in our experiments through the use of Original (O) and Sandy Loam (SL) soil configurations. As shown in table 2.2, these two soil configurations are very similar in their composition, differing by less than 4 percent in their clay, silt and sand contents. However as the scatter plots show (figure 4.5b), there are marginal differences in the correlation between rainfall and beta for those two soil types.
In general, our experiments reveal that agricultural droughts are more likely to occur in soils with higher clay content. This is because clayey soils have low porosity and this reduces the infiltration rate (Pidwirny, 2006). The low infiltration rate for CL soil leads to high surface run-off which reduces the amount of soil moisture available to plants. As already discussed in section 2.2.1 of chapter 2, whenever the soil becomes saturated JULES adds any excess rainfall to the surface runoff. Clayey soils therefore have a higher runoff rate which reduces the amount of soil moisture available to plants, beta, making them more susceptible to agricultural droughts. This is one reason why there were more agricultural droughts in soils with high clay content. On the other hand, soils with higher sand content such as Loamy Sand and sandy Loam from table 2.2 have a more coarse structure which increases the infiltration rate and thus leads to less droughts being recorded by the model. Similar findings have been reported by Beven and Germann, (1982) for sandy soils. This explains why soils with higher sand content produced fewer droughts than clayey soils in this study.

The usefulness of this finding for agricultural planning is that it could help governments and farmers plan the amount of water resources that goes to different places and different farmlands in the event of a drought. At the level of the individual farmer, it is possible for a single farmland to have soils with different clay, sand and silt concentrations. For a government agency in charge of drought planning such as the Ghana irrigation development authority, it will be important to know how to distribute limited water resources to different parts of the country the Northern and Upper East regions used in this or even localities within the regions. With foreknowledge of the soil types that are available, decisions could be made as to which areas to irrigate more and which one to receive less irrigation.
Chapter Six: Conclusions

6.1 Summary of Findings

The results from this study can be summarised as follows;

- TAMSAT does show some skill at replicating the inter-annual variability in rainfall as well as the occurrence of rainfall in the study area when compared with observation data. However, due to the fact that TAMSAT persistently underestimates both rainfall (figure 3.3a) and soil moisture (figure 3.3d) by about 25 percent, there will be a need to improve upon the estimation methods used in generating the TAMSAT rainfall data. For purposes of soil moisture based drought assessments, TAMSAT proves very useful because the underestimation of rainfall does not impact significantly on the values on beta as shown in figures 4.5b and 4.5c and discussed on pages 62 and 63.

- Meteorological wet/dry years do not correspond to agricultural wet/dry years as shown in figures 4.2a, 4.2b, 4.2c and 4.2d. This is because there are other factors that influence the amount of soil moisture available for crop production. There is therefore the need to consider those other factors in the assessment of droughts. Modern advances in computing and modelling allows for the use of land surface models to be used in that direction.

- Even though there were marked differences between the drought assessments based on soil moisture (beta) and that based on rainfall (see figures 4.6a, 4.6b and 4.6c), there isn’t enough evidence from this study to conclude at this stage that drought assessments based on beta is better than traditional drought assessment based on rainfall. It therefore remains a theoretical assumption that because the modelling of beta takes other factors that have impact on soil moisture into consideration, beta-based drought assessments will be better than traditional drought assessment that are solely based on rainfall.

- The type of soil at any given location has influence on the risk of droughts occurring at that location. This risk of an agricultural drought occurring at a location is higher if it has soil with high clay content. If the soil has low clay content then the risk of a drought occurring is lowered.
- The vegetation type and vegetation cover has impact on agricultural drought. The larger the percentage of land surface that is covered with crops, the higher the chances of drought occurring. Land surfaces covered with C4 crops will be more susceptible to droughts than those covered with C3 crops.

6.2 Limitations of this study.

This study has some limitations which need to be addressed in order to improve the results. Four of these limitations are described below.

One of these limitations is the unavailability of data for the model runs. Even though data did exist for the period 197-2011, only data for 1998-2011 could be used because a large portion of the observation data (1970-1997) was found to be faulty. Though 14 years was sufficient for the study, it would have been better to have at least 30 year data.

Ideally, it would have been good to have either in-situ or remotely sensed soil moisture measurements for Tamale and Navrongo for the period of study so that the results from this study could be compared with those soil moisture measurements. However there is no historical in-situ soil moisture data for the study site and satellite estimated soil moisture data was also not readily available when requests were made for them. In the absence of soil moisture data, results from OBS experiments were assumed to be the truth even though there may be errors in the OBS data as shown in figure 3.2a.

Another limitation of this study is how the drought line was defined. The drought line as defined in section 2.4.3 is based on the 25th percentile or lower quartile of mean AMJJA beta. The drought line defined this way, can tell if there was agricultural drought in a particular year or not as shown in tables 4.1, 4.2, 4.3 and 4.4 but it cannot tell the severity of the drought. This can limit the usefulness of the drought index because policymakers would want to know how severe a drought event will be so that appropriate measures can be put in place. Therefore, in its current form, the drought line definition may not be of much help to policymakers.
This study was carried out with JULES version 3.3 as described in section 2.2.1 because it was the version of JULES that was available for the study. Since the release of JULES version 3.3, five updates have been made to the model and the current version is JULES version 4.4. Each update comes with improvement in the model’s ability to represent soil and land surface conditions. It stands to reason that better results could have been obtained if a newer version of JULES model was used for the study.

6.3 Further work

In this study the only satellite based rainfall estimated data used was that from TAMSAT. However as mentioned in the introduction (section 1.3), there are other satellite products available such as those from Tropical Rainfall Measuring Mission (TRMM 3B42) and Climate Prediction Center Morphing method (CMORPH). These datasets could also be used for a similar study and then their performance can be evaluated. Depending on how well they match observations, they could be used for drought monitoring and agricultural risk assessment.

It is also recommended that the definition of the drought used in this study be improved upon so that it can give an indication of the severity of drought events since this will be more useful for policymaking.

New versions of JULES model are available that allows for explicit representation of crops in the model itself without the use of proxies. It is therefore recommended that future studies be carried out using the latest versions of the model as it potentially could lead to better results.
Chapter Seven: References


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