MODIS NDVI satellite data for assessing drought in Somalia during the period 2000-2011

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Abstract

Somalia, the country in East Africa in a region referred to as Horn of Africa is in a civil war, conflict and unrest since 1991. The prolonged conflict increases the impact of droughts in the country which is already prone to drought continuously. This study focused on assessing and monitoring drought in Somalia during the study period 2000-2011, especially drought of 2010-2011 which became a disaster. MODIS NDVI satellite data was mainly used to achieve the purpose of the study in companion with rainfall data from Climatic Research Unit (CRU) 3.1 and Rainfall Estimation (RE) 2.0. The analysis was done at pixel-scale in seven locations as well as at regional-scale. The most important result is that among all drought years during the study period, drought of 2010-11 was the most influence one in its duration (more than a year), intensity (30%-50% negative change) and extension to most parts of southwest Somalia and north and northeast of Kenya. The nature of livelihood (pastoralism); the absence of stability and peace; and the high population density in south of Somalia made the impact of drought catastrophe (crossing the famine threshold) than other parts of the region e.g. east and northeast of Kenya. During the study period, most dry spells started in the second season and continued to the next season e. g. 2003-2004, 2005-2006 and 2010-2011 and was often followed by above normal rainfall. Also, droughts with long duration are less frequent than that with short duration. Second rainy season (Deyr) showed to play a significant role in the interannual variability in Somalia rainfall pattern and then in drought onset. This due to that the peak of NDVI and correlation coefficient between NDVI and rainfall in second season (Deyr) are higher than the first season (Gu). Monthly correlation coefficient between rainfall and NDVI showed to be significant at 99% in most locations (mean of r = 0.40) even thought not very strong (R^2= 0.26) but it becomes stronger with time lag of one month for NDVI. Annual correlation showed to be low and even negative in some locations. In a country like Somalia where reliable data is difficult to obtain continuously, remote sensing data proved to be a significant tool in monitoring and detecting drought components.

Acknowledgements

Dedication

I dedicate my thesis to my mother for her sacrifices throughout my life after my father death and for her endless love, support, encouragement, and inspiration. To my brothers and sisters for their love and support.

To my lovely wife for her support and help throughout my study and to my sweet baby Sama (10-month old).

I love you all.

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Abbreviations

AMSU-B	Advanced Microwave Sounding Unit
AVHRR	Advanced very High Resolution
BADC	British Atmospheric Data Center
BRDF	Bidirectional Reflectance Distribution Function
CIA	The Central Intelligence Agency
CMG	Climate Modeling Grid
CRU	Climatic Research Unit
FSAU	Food Security Analysis Unit
FAO	Food and Agriculture Organization of United Nations
FEWS NET	Famine Early Warning System Network
FSAU	Food Security Analysis Unit- Somalia
GPI	Global Precipitation Index
GTS	Global Telecommunications Station
HDF-EOS	Hierarchical Data Format-Earth Observing System
ILRI	International Livestock Research Institute
ITCZ	Inter tropical Convergence Zone
LP DAAC	Land Processes Distributed Active Archive Center
MCD43C4	A product of BRDF from MODIS land reflectance
MOD12C1	MODIS Land cover
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	The National Aeronautics and Space Administration
NDVI	Normalized difference vegetation index
NOAA	National Oceanographic and Atmospheric Administration
PDI	Precipitation Drought Index
RFE	Rainfall Estimation
SSM /I	Special Sensor Microwave/Imager
SWALIM	Somalia Water and Land Information Management
TS	Time Series
UNDP	United Nations Development Program
WIST	Warehouse Inventory Search Tool

1. Introduction

F Following a vicious conflict and civil war since 1990 after the Somalia's President Siad Barre was overthrown; the country is still without any unified authority and government (Saundry, 2011). This situation in the country, which is already prone to drought, increases the effects of the drought, especially in the south where the fight continues, and makes it very difficult to aid the effected people (Kundell, 2008).

''*In total, 3.7 million people are currently in crisis nationwide; among these, 3.2 million people need immediate, lifesaving assistance (2.8 million in the south). As of early July, 390,000 children under five are acutely malnourished, 170,000 severely; 81 percent of acutely malnourished children live in the south.*'' This is a quote from FSNAU report in Aug. 16, 2011 about Somalia situation (FSNAU, 2011a). A failure of second rainy season of 2010 and a poor rain in first season of 2011 had led the country and the region to the worst drought in Africa since the drought of 1991-92. It crossed the threshold of famine in many parts of the region particularly in south of Somalia and east of Kenya.

Somalia is located in East Africa in a region called Horn of Africa. Most of the country is dry land while some parts of northwest and most of southwest are semi-arid lands which receive a moderate rainfall valid for rain fed agriculture. Most of the country has two rainy seasons: April-June for first season or main season (Gu) and October-November for second season or short season (Deyr). This rainfall pattern is influenced by many factors that control the time of rain and its amount. Inter Tropical Convergence Zone (ITCZ), El Nino Southern Oscillation (ENSO) are the most important factors in Somalia (Metz, 1992; Muchiri W., 2007). ITCZ controls the time for the two rainy seasons and ENSO influences the amount of rain received. During the movement of ITCZ northward or southward, it controls the onset of rain in the two rainy seasons. During the positive phase of ENSO there will above normal rain and during the negative phase there is below normal rain. Rainfall is the most crucial factor climatically in the country as most of the population depends on rainfall for their livelihood (Metz, 1992). Half of the population depends on pastoralism which is influenced by the amount and time of rainfall. In general, rainfall is characterized by its variation in time and amount and by its location in distribution. The country is frequently exposed to drought, occurring moderately every 3-4 years and severely every 7-9 years (Kundell, 2008).

Drought is a complex environmental disaster which can be defined as the rainfall decrease from its normal average (Wilhite, 1992). Drought is characterized as a slow process, can happen everywhere and anytime and prolongs from months to years (Chang and Wallace, 1987). The characteristics of drought which make it complex include; lack of universal definition; impacts can effect outside of suffered region; and its impacts accumulate slowly over long time and might continue after drought terminates. Time and distribution of rains during the growing seasons, duration and intensity of rain, rain onset and end, temperatures, low relative humidity, and high winds play important parts on drought occurrence (Mishra and Singh, 2010). Drought has important components: onset, duration and intensity which should be included in any study focused on drought monitoring. Drought has many severe impacts on society and environment and they become more and more complex among other natural hazards especially with a changing climate (Wilhite et al. 2007). The effect of climate change

is not by decreasing the average rainfall received in a region but from widening standard deviation and climate extreme events become more common and so is drought (Clark et al., 1999).

Recently, the advance in remote sensing data both spatially and temporally makes it possible to use this data for drought monitoring regionally and globally. Over the last few years, satellite data has become a main source to detect changes of the environment which provides a comprehensive view of changes that cannot be observed from Earth's surface. Remote sensing is essential when there is a lack of meteorological data or it is inaccurate or difficult to obtain, especially in a country like Somalia where there is no essential meteorological data; it is the only way to monitor drought and its aftermath's assessment. Remote sensing data particularly MODIS Normalized Difference Vegetation index (NDVI) data is used intensively for studying vegetation change worldwide. It is one of the most successful attempts to detect vegetation greenness globally. Remote sensing provides global data every one to two days continuously, which is superior all other known data.

Objectives

The overall purpose of this study is to assess and monitor the drought in Somalia during the period 2000-2011 with more focus on the drought in 2010- 2011 using remote sensing data. Time series analysis of mainly MODIS NDVI is used to achieve the aim of the study. In order to succeed in this purpose, the following sub-objectives are studied:

- Illustrate the characteristics of the 2010-11 droughts which made it different from the previous droughts.
- Study the characteristics of drought in the regions to increase the knowledge about drought in the region especially in Somalia.
- Study the seasonal pattern of vegetation which might explain the drought event in the region and its drivers.
- Study the relationship between rainfall and NDVI data monthly, seasonally and annually.

Time series analysis of vegetation change obtained from MODIS NDVI for period 2000-2011 and different approaches using different mathematical equation were used to achieve the purposes of this study. Such phenomenon is not easy to analyze because of many factors, which were not available currently, influence the response of vegetation to decreasing in rainfall and have the same impacts as drought such as fire, flood, and overgrazing. I assumed that the decreasing value of the used vegetation index is due to drought if that appeared in all the study locations or at least in most of them. Pattern of rainfall and relationship between the rainfall and NDVI was calculated monthly, seasonally and annually at local-scale. To monitor and assess drought, three components were studied: onset, duration, and severity or intensity. To detect drought onset and duration, mean monthly NDVI and rainfall were plotted against the long-term monthly average and also monthly anomaly was calculated. Drought intensity was detected using two methods: setting threshold and percent of change.

2. Background

The area of interest in the current study is Somalia and some surrounding parts of neighboring countries: Ethiopia and Kenya (figure 1). Mogadishu is the capital and the country has total area of 637,660 km^2 and the total population as estimated in July, 2011 is 10.3 million approximately, of which 65% live in rural areas (Kundell, 2008). Somalia has been without a union government since 1991 after the overthrow of President Siad Barre. A civil war and conflicts between clan leaders in the country has divided it into some internationally unrecognized and unstable parts. In the north there are two autonomous parts; Puntland, and Somaliland. The situation in the south is worse and much more complex because it is divided among many groups and the Transitional Federal Government (TFG) (Saundry, 2011). Half of the population depends on pastoralism which is governed by the amount and time of rainfall. During the drought years such as 1974-75, 1984-85, and in January 2000, many people suffered even to point of malnutrition and starvation, and were displaced from their areas (FSNAU, 2011b). In 2010 drought hit the region but it became a disaster mainly in south of Somalia.

2.1.1. Geography

Somalia is the easternmost country of Africa and located in a region referred to as The Horn of Africa. Somalia extends from the Equator in the south, northward to the Gulf of Aden. The country can be divided into different physio-geographic zones distinguished by topography: northern coastal zone which has the highest variation in temperature and the driest zone in Somalia (Kundell, 2008). The Karkaar Mountains in the north occurs close to the Gulf of Aden and extends from east
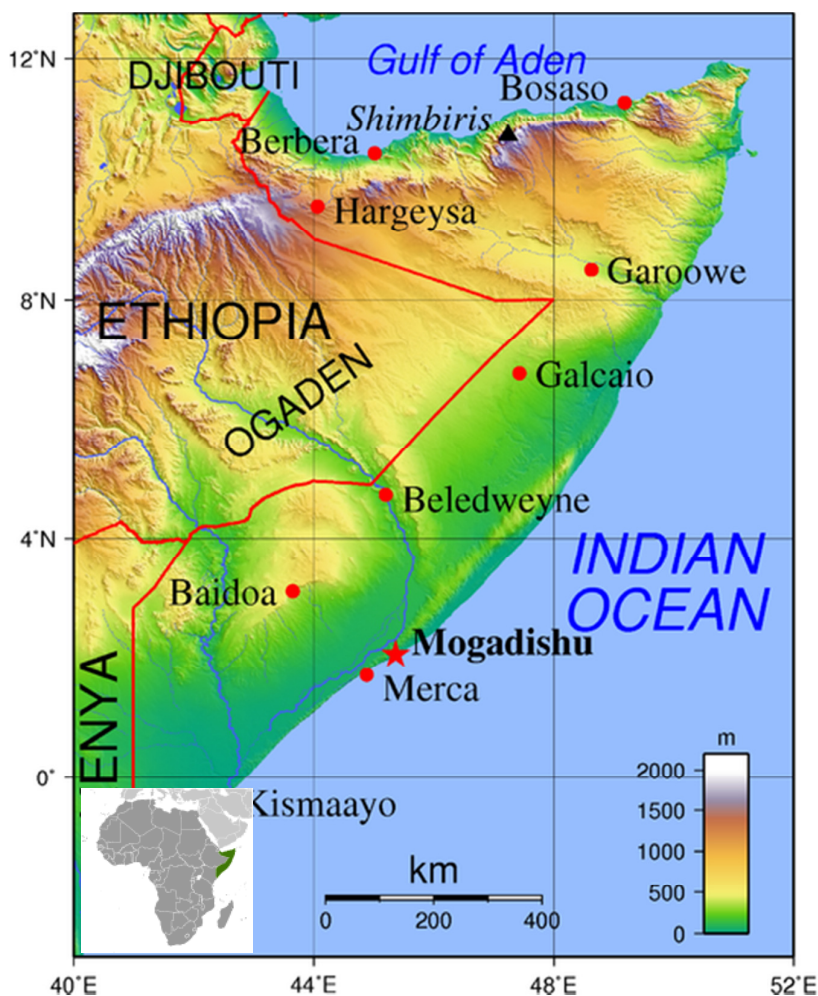
Figure 1 Somalia topography map and location of Somalia in Africa in the small corner map.(HRW world atlas, 2007)

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to west, with its highest point Shimbiris (2,416 meters above sea level) (Saundry, 2011). Interior Plateaus (increasing gradually to roughly 900 m) cover most of the central and southern part while plains border the coastline and widest in the south. In the south, there are two perennial rivers: Jubba and Webe Shebele Rivers which come from the Ethiopian Plateau and flood in some years when there is a heavy rainfall in Ethiopia. The plain between the rivers in the south has the highest agriculture potential in Somalia and frequently affected by flood (Kundell, 2008). Somalia has the longest coastline in Africa (3,025 kilometers) and has an important position between south Asia, southwest Asia and East Africa (Encyclopedia Britannica Online, 2011). The country and region are frequently prone to drought, moderately every 3-4 years and severely every 7-9 years (Kundell, 2008). On top of that, it has one of the highest undernourishment rates in the world with around 70%. During the 90s drought years, more than 300,000 people died from hunger and malnutrition. Also, about 1400 people died and around 1 million were indirectly affected from floods in 1997-98.

2.1.2. Climate

Due to its close location to the equator and low precipitation, Somalia has some of the highest mean annual temperatures in the world with an average annual daytime temperature of 27°C (Encyclopedia Britannica Online, 2011). Basically, hot weather dominates throughout the year in Somalia except in the northern highland (Metz, 1992). In the north and central parts, variation in temperature is high, from freezing in winter in the Karkaar Mountains close to the Gulf of Aden to around 45°C in the interior plateau in summer. In the south, the variation in temperature is lower and ranges from 20°C in the coldest months to about 30°C in the hottest months which are February to April. The coastal region is usually 5-10°C cooler than the inland areas because of a cold offshore current.

The country can be divided into two climatic zones with an arid zone in the northernmost and central regions, and a semiarid zone in small area in northwest, northern mountains and most of southwest (Metz, 1992). Rainfall is the most crucial factor in the country as most of the population depends on the rainfall seasons for their livelihood (Metz, 1992). The moderate precipitation in the northwest and southwest is sufficient for rain fed agriculture. However, most of the other parts of the country have low rainfall suitable only for pastoralism, which is practiced by half of the population.

Four seasons occur in the country: Two rainy and two dry seasons. The *Gu* is the main rainy season which lasts from April to June and is followed by *Xagaa* or *Hagaa*, the short dry season extending from July to September (Kundell, 2008). Some coastal areas in the south receive a significant amount of rainfall during the *Xagaa* season because of e monsoon wind. The other rain season is *Dayr or Deyr* which is the short rainy season in October and November and most of the south receives a significant amount of rainfall during this season while the northern part receives less rainfall due to the influence of dry air from the Arabian Peninsula. *Deyr* is followed by the second and main dry season, *Jilaal or Jilal,* that extends from December to March (Encyclopedia Britannica Online, 2011). In *Jilaal* the north-east monsoon wind produces some precipitation in the highlands in the north (Mutua and Zoltan, 2009).

Indeed, the country has one of the highest inter-annual variations of precipitation in Africa (Kundell, 2008). The mean annual precipitation is 282 mm with only about 50 mm in

the north coast, 500 mm in the northern highlands, about 150 mm in the interior plateau and 350-500 mm in the southwest. However, the precipitation is characterized by its variation and takes a form of showers. During the short rainy months, the vegetation grows in the most of the land especially in the plateau. Figure 2 shows rainfall distribution map of Somalia and we can see that the southwest region and small parts in northwest region receive a moderate amount of rainfall during the rainy seasons.

Annual potential evapotranspiration (PET) is more than 2000 in the north especially in north coast of Gulf of Aden with 2900 mm (Mutua and Zoltan, 2009; Kundell, 2008). In south, it is about 1500-2000 near the coast. PET increases from south to north due to increasing of temperature which make PET greater than precipitation in most of the country. In some locations such as Baidoa and Jilip in the south and Borama in the north, rainfall exceeds 0.5 PET in the rainy seasons giving a chance for rained agriculture (Mutua and Zoltan, 2009; Muchiri W., 2007).

2.1.3. The variables that influence the rainfall in Somalia

Studies focusing on Somalia's climate are rarely available through scientific journals because of current situation in the country. However, rainfall pattern has been studied as part of East Africa region studies which has similar pattern. Somalia has bimodal rainfall seasons; the first and the main season (*Gu*) and the second short autumn season (*Deyr*). These rainy seasons are influenced by many factors globally and locally (Metz, 1992; Muchiri, 2007). These factors include the Inter Tropical Convergence Zone (ITCZ), El Nino Southern Oscillation (ENSO), the Indian Ocean circulation, the Arabian Peninsula high and the Ethiopian plateau. Moreover, the location of Somalia close to Kenyan and Ethiopian highlands decreases the rainfall further more (Metz, 1992). I will shortly describe two main variables that influence the region's climate.

Table 1 ENSO events. Source: Golden gate for weather services (2012) based on Oceanic Nino Index (ONI).

El Niño			La Niña		
Weak	Mod	Strong	Weak	Mod	Strong
1969	1951	1957	1950	1955	1973
1976	1963	1965	1954	1970	1975
1977	1968	1972	1956	1998	1988
2004	1986	1982	1962	2007	1999
2006	1987	1997	1964		2010
	1991		1967		
	1994		1971		
	2002		1974		
	2009		1984		
			1995		
			2000		
			2011		
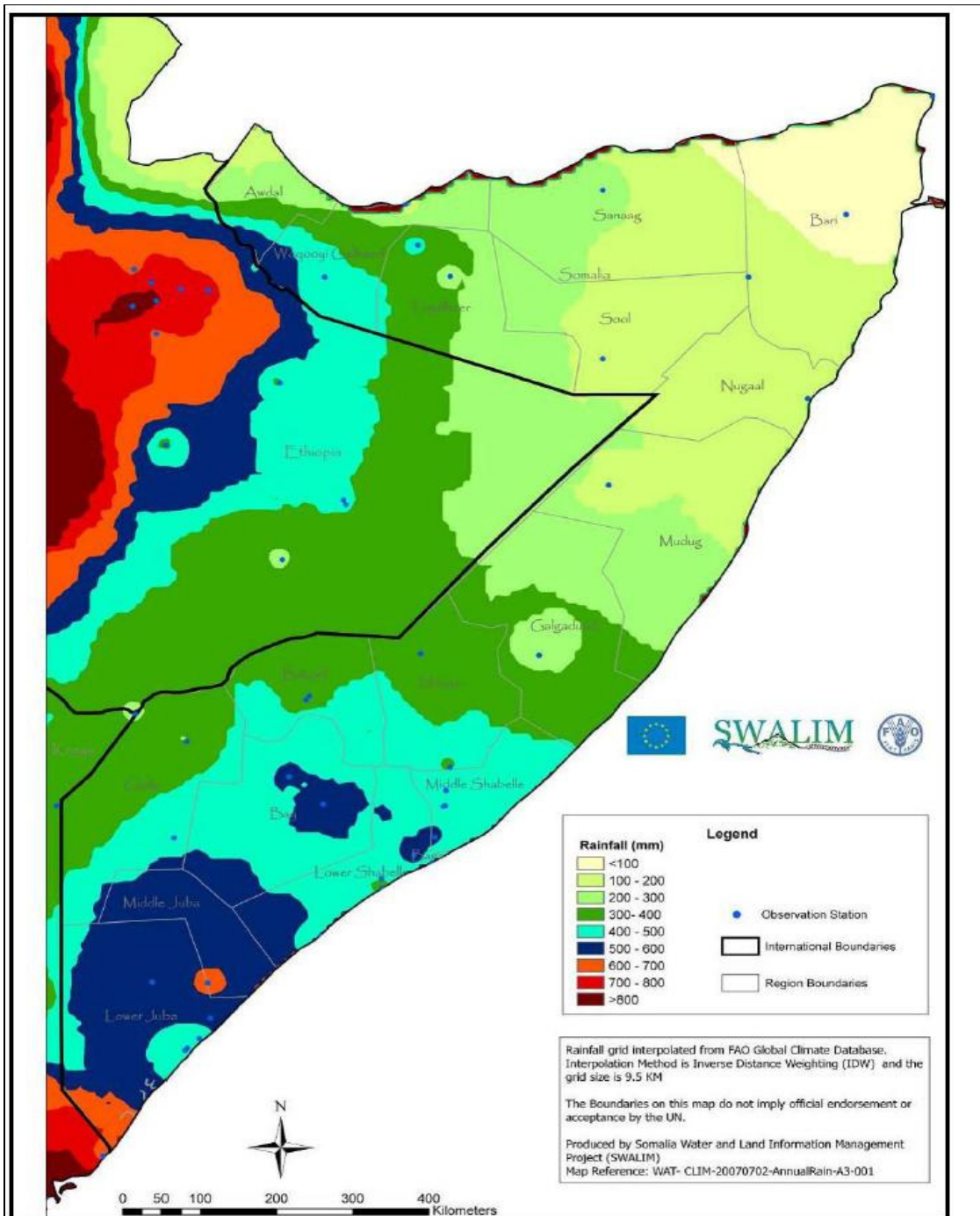
Figure 2 Rainfall distribution in Somalia (Muchiri, 2007). Only the northwest and south of Somalia receiv
a moderate rainfall valid for agriculture.

2.1.3.1. Inter Tropical Convergence Zone (ITCZ)

ITCZ is one of the components of the global circulation system. Figure 3 show the normal oscillation of ITCZ during January and July (Mutua and Zoltan, 2009). The spatial oscillation in East Africa is large which drives it to cross this region fast. This fast movement over the region introduces high variability and unreliability of rainfall during the rainy seasons. During March and September, there is a solar heating in the tropical zone because sun is over the

country forming a low pressure which brings convectional precipitation (Muchiri, 2007). Trade winds move southwesterly in the northern hemisphere while in southern hemisphere they move northwesterly to the zonal belt of low pressure. Cloudiness and intensive precipitation occurs in the point where trade winds converge. ITCZ usually moves over the region a month later in April and October when the peak of the two rainy seasons *Gu* and *Deyr* occur. In July the sun is over Tropic of Cancer forming a high pressure in the south and low pressure over Arabia and India. The trade winds become south-west monsoon over southwest of Somalia which receives a significant amount of rainfall during summer. In January, the sun is over the Tropic of Capricorn and trade winds have northeast direction and pass over Arabian Peninsula and it is usually dry (Muchiri, 2007; Sato et al., 2007).

Figure 3 The position of the ITCZ during January and June. Source: Mutua and Zoltan, 2009.
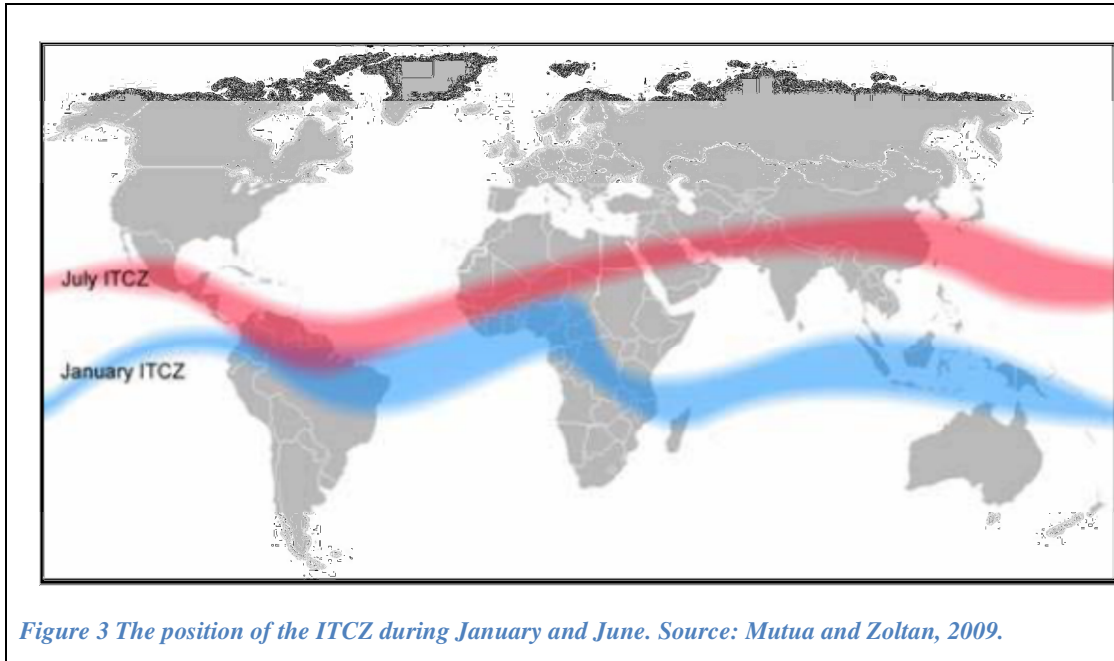
2.1.3.2. El Niño Southern Oscillation (ENSO)

ENSO is the effect of sea-surface temperature of equatorial Pacific Ocean on the global atmosphere (IRI, 2007). El Niño is the positive phase when the equatorial Pacific is warmer than average, while La Niña is negative phase when it is cooler than average. The seasonal rainfall and temperature in many regions of the world are influenced in a regular way by the effects of The ENSO system. The ENSO influences the climate in the region of East Africa through teleconnections. ENSO is associated with above average rainfall in the short rainy season (October to December) during the positive phase (Plisnier et al., 2000). In the negative phase (La Niña) it is associated with below average precipitation. Table 1 shows the events of ENSO (Golden gate for weather service, 2012).

2.1.4. Land cover and land use

Most of the country is in the arid zone having only 1.64% is arable land which makes it unproductive (Kundell, 2008). Land cover is determined by the climate (especially rainfall), elevation, soil characteristics, and population (Metz, 1992). Majority of the country is covered by permanent pastures with an area of 43 million hectares (ha). The cultivated area was 1,071,000 ha in 2002 out of which 26,000 ha are covered by permanent crops and the rest are

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seasonal planting. In south there are two growing seasons, first one from April to July and second one from the end of September to January (FSNAU, 2011). In the northwest part there is only one long growing season from in April to October (Eklundh, 1996). Figure 4 shows the land cover classes derived from MODIS land cover (MCD12Q1) in 2004.

2.1.4.1. Arid region

Most of north and central parts of Somalia are dry and covered by open shrubs due to low amount of rain received (Metz, 1992). The dry vegetation appears as scrub-covered such as Acacia with some bushes and grasses which grow during the rainfall season and close to intermittent watercourses. Some tall trees like tamarisk grow along the banks of dry valleys. Generally, the vegetation decreases from northern highland to northeast and from north to the central of Somalia as the aridity increases.

2.1.4.2. Semi-Arid zone

Northern highland elevation ranges from 1800 to 2400 m and receives more than 500 mm rainfall. Vegetation becomes dense and closed shrub appears and woodlands of Juniper and candelabra euphorbia are common; some arid trees such as boswellia and commiphora also can be found (Metz, 1992). This vegetation offers a good condition for nomadic pastoralism especially in rainfall season. Basically, vegetation increases westward as rainfall increases where some dry woodland and grassland exist.

South of Somalia has the richest biodiversity in the country (Metz, 1992). Most of arable lands are located in this region as it receives moderate rainfall and the two perennial rivers Shebelle and Jubba are in this part. The area between these two rivers is agriculture land and crops are grown such as sorghum, corn, vegetables and some fruits (Kundell, 2008). Other land cover might be savanna, open woodland and grass which supply rich pastures. Along the Indian Ocean coast, grass and scattered shrub cover the land and mangrove forest can be found and further southward to Kenya border, some dry evergreen forest grow.

Figure 4 *Land cover and vegetation of the region. Most of the north and central parts of Somalia are dry and only open shrubs can grow. In southwest of the country, north highland and some areas in northwest are semi-arid. Vegetation is denser and even evergreen and mangrove forest and can be found. Image derived from MODIS land cover MCD12C1, 2004 (LP DAAC, 2010a).*
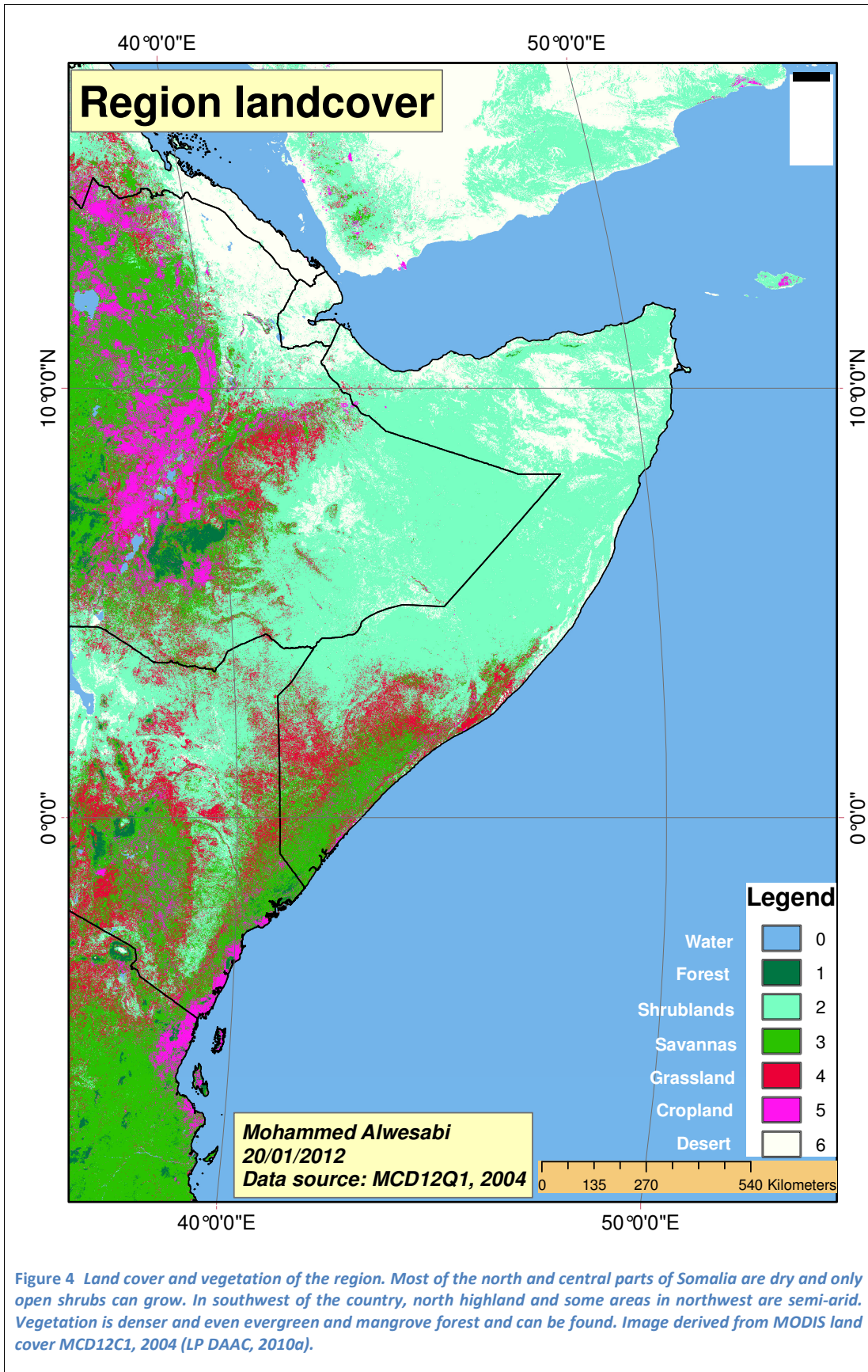
The majority of people in Somalia practice pastoralism as a main source of livelihood. Nomadic and sedentary pastoralists raise camels, goats, sheep and cattle (Encyclopedia Britannica Online, 2011). Their livestock depends entirely on the rainfall seasons and this might explain the severe impacts of prolonged drought in the country. Other activities of people include agriculture, fishing and trading. Mismanagement and lack of appropriate land use with, overgrazing and logging have heavily damaged the vegetation in Somalia, especially in northern Somalia (Encyclopedia Britannica Online, 2011). In south region, most of forest land has been destroyed, especially mangrove forests. The effects of damaging in vegetation not only affect the diversity of the country but also extend to the livestock which threatens the life of hundred thousands of pastoralists.

Land cover and land use in Somalia and the region is shown in figure 4. The image is derived from MODIS land cover 2004 (LP DAAC, Land Cover MCD12Q1, 2010). Most of the north and the central parts are covered by open shrub lands with some grass vegetation in the valleys during the rainy seasons. Towards south and southwest, vegetation becomes denser and some grasslands and savannas can be found as well as some croplands.

2.2. Drought

2.2.1. Overview

Drought is a complex disaster which lacks a universal definition, develops over time and is with unobvious impacts (Wilhite, 1992). The World Meteorological Organization (WMO, 1986) defines drought as 'a sustained, extended deficiency in precipitation.' and the Food and Agriculture Organization (FAO, 1983) define it as 'the percentage of years when crops fail from the lack of moisture'. Drought is a slow-onset natural hazard, mostly related to decline in the amount of rainfall in an area for a period of time (a couple of months, season and even years) (Mishra and Singh, 2010). Drought differs from other natural hazards such as floods and cyclones as its impacts accumulate slowly over a long time and they might continue after drought termination (Wilhite, 1992). It is often difficult to determine the beginning and the end of a drought. Drought differs from aridity which is a distinctive permanent climate in a region characterized by a low precipitation while drought is an impermanent phenomenon which can occur anywhere and anytime. In addition, drought differs from heat waves that continue for a few weeks and associate usually with high temperature and dry weather while drought continues for a longer time (Chang and Wallace, 1987). Drought often associates with high temperature, high wind and low relative humidity.

Drought should be defined relative to its long-term average of rainfall or greenness to enable studies of its characteristics (Mutua and Zoltan, 2009). Basically, drought is characterized by its three components: first is the drought onset and end, second is the drought duration, which is the time period between drought onset and end in order of months or years, and third is the drought severity or intensity, which is the severe shortage of the water availability with respect to the normal. These definitions normally are conceptual definitions rather than operational definition of drought, which are often regional specific. Operational definitions need analysis of hydro-meteorological information for developing drought policies, monitoring and mitigation strategies.

Scientists often classify drought into four classes depending on the parameters used to describe it. According to American Meteorological Society *(*2004) and Mishra and Singh (2010) drought classes are:

Meteorological drought: defines the decrease in the amount of rainfall and duration of the drought.

Hydrological drought: describes the impacts of declined period of precipitation on the surface and the subsurface water resources.

Agricultural drought: links the impacts of drought and soil moisture declination which influence the failure of agricultural crops.

Socio-economic drought: refers to the failure of water supply to meet the water demand. Socio-economic drought usually describes the indirect impacts of drought.

In this study, agricultural drought was mainly studied using remote sensing data. NDVI data indicates vegetation conditions rather than rainfall pattern. Meteorological drought was studied also using rainfall data.

2.2.2. Drought Impact

Drought has impacts on many aspects of societies and often leads to severe effects which spread over larger area than the actual damaged region (Wilhite, 1992). Direct impacts are usually of biophysical nature such as reduced crop yield, pastures and water levels and increased livestock mortality rates and fire risk. Indirect impacts are results of direct impacts associated with socioeconomic and long-term change such as decreased income for farmers and agro-pastoralists, increase in food prices and unemployment (Wilhite at el., 2007, Sivakumar, et al, 2011). Among other natural hazards, drought had the greatest effects during the 20th century globally (Obasi, 1994).

A societal vulnerability to drought is a result of the relationship between the water supply (precipitation and water resource) and the water demand or human use. When the demand exceeds the water supply and water resource, the vulnerability of a society increases. The vulnerability of a society to drought is continually fluctuating in response to increasing population, land use changes, technology, government policies, and many other factors. Societies that depend on practicing pastoralism, typically Somalia, are often vulnerable to natural hazard like drought, especially with non-stable political situations.

Somalia as all the region's countries has a long history of drought. Prolonged drought hit the country many times in 1974-75, in 1984-85, and in the last decade the drought happened in 2005, 2008 and the worst in 2010-11 (Metz, 1992; Hastenrath et al, 2007; Hastenrath et al, 2010; FEWS NET, 2011). According to the Kundell (2008) the country is frequently prone to drought, occurring moderately every 3-4 years and severely every 7-9 years. As the results, millions of people suffer from famine, displacement, acute malnutrition and rates of crude mortality.

The global warming due to increased rates of greenhouse gases in the atmosphere will intensify the hydrological cycle (Milly et al., 2002) as the mean surface temperature of the Earth increase. An increase in temperature globally will lead to increase in precipitation, evaporation, and runoff (Clark et al., 1999). The impact of climate change on drought is not

the change in the average but increase of extreme events. The effects of climate change on drought intensity and duration will vary between regions according to different scenarios of the future climate (Mishra and Singh, 2010). Drought prediction encounters many difficulties; it needs long-term and large-scale data as well as weather variability extreme events data (Schubert et al, 2007). Remote sensing technology offers large-scale data while paleoclimatic records offer a long-scale data.

2.2.3. Drought drivers in Somalia

There is a strong relationship between rainfall in the region and El Niño-Southern Oscillation (ENSO) phenomenon (Plisnier et al., 2000). During El Niño events, region receives above normal rainfall and during La Niña event, it receives below normal rainfall. Another possible reason for drought in East Africa and Somalia is the surface westerlies. During boreal autumn short rain, the surface westerlies sweep the central-equatorial Indian Ocean and it is influenced by a powerful zonal circulation cell (Hastenrath et al, 2007). The steep eastward pressure gradient between Indonesian low pressure and East Africa high pressure increases the speed of westerlies; with fast westerlies, rainfall in East Africa is deficient.

2.2.4. Drought Monitoring

As impacts of drought increase there is a growing need for monitoring and predicting drought. Scientists have developed many indices to identify and monitor drought onset, duration and severity which will provide information for decision makers to decrease and mitigate its impacts. Drought indices can be divided into two main categories, depending on the data and parameters used. However, drought parameters used should be able to detect and monitor drought for different time scales; month, season and year (Mishra and Singh, 2010). Annual analysis can identify the behavior of drought in a region but monthly and seasonally analysis assess drought impacts on different aspects e.g. agriculture and water supply (Panu and Sharma, 2002). These indices include meteorological and remote sensing indices, each with its own strengths and weaknesses.

2.2.4.1 Meteorological indices:

Most of meteorological drought indices are rainfall-based with or without some other meteorological variables such as temperature and soil moisture. For example of these indices: the Palmer Drought Severity Index (PDSI – Palmer, 1965) which is the oldest but relatively complex and broadly used in United States; the Decile index (Gibbs and Maher, 1967), which is used in Australia and quite easy to calculate; the crop moisture index (CMI; Palmer, 1968); the surface water supply index (SWSI; Shafer and Dezman, 1982); the China-Z index (CZI), which is used by the National Metrological Center of China (Wu et al., 2001) and the standardized precipitation index (SPI – McKee et al., 1993) which is widely used in the world (Tadesse, 2011; Morid et al, 2006, Mishra and Singh, 2010). Wu et al (2001) evaluated SPI with Z-Score and CZI and found that the last two indices provide similar results as SPI but they are relatively easy to calculate. Morid et al (2006) evaluated seven indices and found SPI and EDI are able to detect the drought onset but EDI does respond better to emergence of drought. Mishra and Singh (2010) discussed the evaluation of different indices based on

scientific papers and found that the regional performance determines the preference of an index.

2.2.4.1 Remote sensing indices:

Remotely drought indices include vegetation indices based on vegetation reflectance such as the Normalized Difference Vegetation index (NDVI), which was first developed by Rouse et al. (1974); and Tucker (1979). NDVI has been studied intensively and it considers the most popular vegetation index. Other vegetation indices were developed recently from NDVI: Anomaly of Normalized Difference Vegetation Index (NDVIA) developed by Anyamba et al. (2001), Standardized Vegetation Index (SVI) developed by Liu & Negron-Juarez (2001); Peters et al. (2002), and Vegetation Condition Index (VCI) developed by Kogan (1990) (Bayarjargal, et al, 2006). Another remotely drought indices are based on the brightness temperature of the surface derived from thermal band of NOAA-AVHRR or combined between temperature brightness and NDVI. This includes temperature condition index (TCI) developed by Kogan (1995), vegetation health index (VHI) developed by Kogan (1997, 2000), Kogan et al. (2004) and Drought Severity Index (DSI) developed by Bayarjargal et al. (2000) (Bayarjargal, et al, 2006). In addition, there are some other indices which were developed using different variables such as soil heat inertia index which based on the energy balance model of land surface (Hou et al, 2007). The normalized difference water index (NDWI) was developed by Gao, (1996) from the NIR and short wave infrared (SWIR) channels that reveal changes in both the water content and spongy mesophyll in the canopies (Mishra and Singh, 2010).

With advanced remote sensing technology, monitoring and assessing drought becomes possible regionally and globally. Remote sensing is essential when there is a lack of meteorological data, inaccurate or difficult to obtain the data. The meteorological indices depends on the spatial resolution and quality of available rainfall data and only represent one component of the surface hydrological cycle e.g. rainfall. Therefore, they often cannot capture the effects of other components inserted to the cycle such as irrigation (Anderson et al, 2011). Satellite remote sensing provides continually a high spectral resolution data over large area. Another advantage of remote sensing data is that the data is provided globally without restriction. It makes it possible to monitor the drought in a country such as Somalia where the other data is difficult to obtain. Vegetation indices from MODIS have been sown a good correlation with Gross Primary Productivity (GPP) across sites in Africa (Sjöström et al, 2011).

A comparison between different drought indices based on remote sensing shows that there is none of the major indices is inherently superior to the rest in all circumstances but some indices have advantages spatially (Tadesse, 2011). There is still need for a comprehensive study to evaluate the performance of these drought indices, especially in semi-arid and arid zone because of the frequent occurrence of drought (Bayarjargal, et al, 2006).

However, in current study NDVI was used due to its availability, relatively easy to use and is available through websites from different sensors e.g. NOAA AVHRR since 1981 and MODIS since 2000. It has been used to monitor vegetation conditions which provide early detecting of drought (Mutua and Zoltan, 2009). NDVI is a practical tool for drought

monitoring at regional and global scale for long time scale (1981- present). Several studies used the using NDVI for drought monitoring (Peters et al, 2002; Eklundh and Olsson, 2003; Gu et al, 2007; Mishra and Singh, 2010). The relationship between NDVI and rainfall has been found to be strong by many scientists e.g. Peters et al (2002) and Martiny et al (2006); but Eklundh (1998) found that rainfall only explained 10% and 36% for 10-day and monthly NDVI, respectively, using AVHRR data. The latter removed the influence of autocorrelation from the data which might increase the correlation between rainfall and NDVI.

2.3. NDVI

2.3.1. Overview

Normalized difference vegetation index (NDVI) which was developed by Rouse et al. (1974) and Tucker (1979) is the first index to monitor vegetation, using data from satellite remote sensing and is used widely in vegetation monitoring. It is one of the most successful attempts to detect vegetation in a simple way and it is used intensively around the world to monitor the vegetation change and vegetation phenology. It is the normalized difference of the reflectance between the near infrared (NIR) and visible red channel. Healthy vegetation absorbs radiation relatively high in the visible red band and reflects significantly high in the NIR band in the so-called Photosynthetically Active Radiation (PAR) region of the electromagnetic spectrum (Mutua and Zoltan, 2009). NDVI measures the changes in chlorophyll content. It has the following formula:

$$\frac{[\rho NIR - \rho RED]}{[\rho NIR + \rho RED]} \tag{1}$$

Where ρNIR and ρRED, are the spectral reflectance in the NIR infrared channel and red visible color channel, respectively, of the satellite sensor (Tucker, 1979). NDVI has values ranging from -1 to 1; that represents the greenness of the vegetation canopy and it is always that vegetation takes values 0.1 to 1 while water, cloud, snow and other land covers tend to take lower or negative values. Higher NDVI values close to 1 reflect healthy vegetation or higher vegetation (denser) while lower values close to 0.1 indicate stressed or less vegetation (less greenness). NDVI was originally obtained from advanced very high resolution radiometer (NOAA/ AVHRR) images since 1981 (Kogan, 1995) and from 2000, the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Terra and Aqua Earth Observation System satellites began obtaining images with improved radiometric, spatial resolution and larger number of channels compared to the AVHRR (Justice et al., 2002).

2.3.2. NDVI limitations

NDVI has limited sensitivity to vegetation saturation in closed canopies as well as effects of soil background at low vegetation cover and atmospheric aerosols (Huete et al., 1994; Wang et al., 2003). Non-climatic variation may affect the NDVI values under similar conditions (Kogan, 1987) which might relate to the non-homogeneity of vegetation due to the different resource in the soil or to inherent genetic characteristics. Also, stressed and damaged vegetation due to other climatic conditions, e.g. flood, may be detected as drought impacts (Kogan, 1995). Another limitation is that there is a clear time lag between the response of NDVI to rainfall deficit which is often 0-2 months, most likely 1 month (Eklundh, 1998; Peters et al, 2002).

3. Data and Material

In this study I used MODIS NDVI and rainfall data mainly to monitor the drought in Somalia from February 2000 to August 2011. Some other data from different resources available through internet were also used, such as: rainfall, land cover, wet days, and population

3.1. MODIS NDVI

Moderate Resolution Imaging Spectroradiometer (MODIS) sensor is onboard of NASA's Terra and Aqua platform satellites, launched in December 18, 1999 and on May 4, 2002 respectively (NASA, 2011). Terra and Aqua are sun-synchronous satellites with polar orbits pass the earth from north to south with 98º inclination and ascend across the equator in the same time locally in the morning for Terra and in afternoon for Aqua. MODIS is considered to be a valuable resource for monitoring the ecosystem and environment (LP DAAC, 2010b). It provides images in 36 spectral bands between 0.405 and 14.385 µm for the whole earth, every one to two days with a viewing swath width of 2,330 km (NASA, 2011). MODIS from both Terra and Aqua provides series of global products (land, atmosphere and oceans) at different spatial resolutions 250, 500, 1000 and 5600 m in HDF-EOS (Hierarchical Data Format-Earth Observing System) format.

Some features make MODIS one of the best resources for remote sensing of Earth Observation (ILRI, 2011).

1. MODIS covers the entire Earth and can be obtained easily by users;

2. It is more frequent than Landsat 7 and higher spatial resolution than AVHRR;

3. It is available at different spatial resolutions (250, 500, 1000, and 5600 m) and different time-scale combinations (8-day, 16-day and 32-day);

4. A significant work has been done to filter the data and remove the effects of clouds and atmospheric aerosols.

MODIS land reflectance (MCD43C4) nadir BRDF- Adjusted Reflectance 16-Day L3 0.05Deg CMG product is used in the current study. In this product, a bidirectional reflectance distribution function (BRDF) is used to model the values as if they were taken from nadir view (LP DAAC, 2010b). Acquired images have 5600 m (0.05°) spatial resolution using a latitude/longitude Climate Modeling Grid system (CMG). They are combined products from both Terra and Aqua, which provides the best quality. The images are produced to represent every 8 days but they are acquired within 16 days (i.e., image of 2001001 Julian day is acquired in the period 001-016 and for day 2001009 is acquired from 009-024). The Data used in this study were downloaded from the website of Land Processes Distributed Active Archive Center (LP DAAC) using the Warehouse Inventory Search Tool (WIST). Images for the region have coordinates of 30 to 55° longitude and -5 to 15° latitude for a period from February 2000 to August 2011.

NDVI value in East of Africa

NDVI value

	-1.1 - -0.07
	-0.07 - 0.15
	0.15 - 0.3
	0.30 - 0.50
	0.50 - 0.87

**NDVI image
25 November 2001
Image below is the
corresponding data
2010**

0 75 150 300 450 600
Kilometers
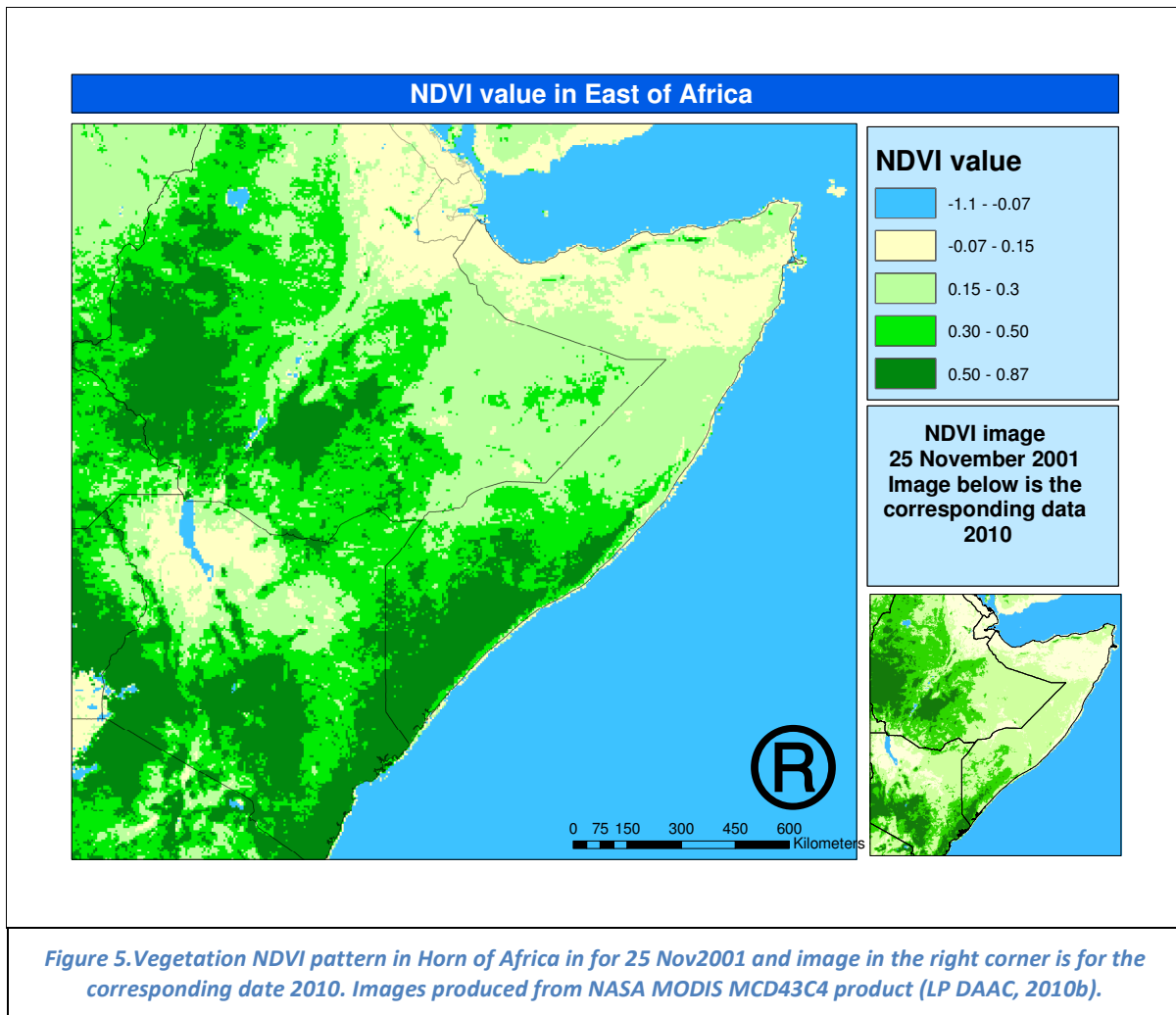
Figure 5.Vegetation NDVI pattern in Horn of Africa in for 25 Nov2001 and image in the right corner is for the corresponding date 2010. Images produced from NASA MODIS MCD43C4 product (LP DAAC, 2010b).

Figure 5 shows the MODIS NDVI (MCD43C4) product for two different dates over Horn of Africa and Somalia. Image A is in November 25, 2002 during the peak of the second rainy season and B is in the corresponding date in 2010. In image of 2010, greenness value is less in southwest of Somalia and east of Kenya.

3.2. Rainfall data

Rainfall data was obtained from two different resources: data from Climatic Research Unit (CRU) 3.1 for period 2000-2009 and Rainfall Estimation (RFE) 2.0 data for the last two years 2010 and 2011.

3.2.1. CRU rainfall data

CRU TS 3.1 is a database of many climatic parameters such as precipitation, daily mean temperature, diurnal temperature range, monthly average daily maximum temperature, vapor pressure and wet day frequency based on gauge station measurements (Phil Jones and Ian Harris, 2008). This database has resolution grids of 0.5° and contains monthly data covering the period 1901-2009. They were originally produced and held by University of East Anglia-Climatic Research Unit (CRU) but in 2007 the British Atmospheric Data Center (BADC) started to provide a long-term support for these databases.

CRU precipitation data was calculated in two procedures: first, the anomaly time series for each station is calculated relative to 1961-90 (25% missing values tolerance) (Mitchell, 2004). Second, the anomalies were added to the 1961-90 grids. Interpolation is used to give the best estimation of the spatial resolution for each dataset grid. The more network stations that exist in a region, is the better estimation for the climate parameter. Network stations that are used in the calculations change from time to time depending on the situation of the stations. Therefore, for a country like Somalia, where meteorological stations are almost not exist or not working correctly, the absence of a single station may have a significant effect on the time-series at a close grid-box.

3.2.2. Rainfall Estimation data

CRU precipitation data covers only the period 1901-2009, therefore there is a data gap for the last two years 2010 and 2011. Then the African Rainfall Estimation data 2.0 was used which started from 2001 and it is provided by FEWS NET Africa Data Portal (FEWS NET, 2011). The African rainfall estimation 2.0 uses algorithms for four types of input data which can briefly be mentioned as follows:

1. Real daily measurements data from GTS Global Telecommunications Station rain gauges for up to 1000 stations.
2. Data from The Advanced Microwave Sounding Unit (AMSU-B), which estimates precipitation up to 4 times per day.
3. Special Sensor Microwave/Imager (SSM/I) satellite rainfall estimates up to 4 times per day (governed by ascending and descending Defense Meteorological Satellite Program polar satellite tracks).
4. Precipitation estimates on a half-hour basis are derived from Global Precipitation Index (GPI) data from Meteosat IR cloud top temperatures.

Dinku et al, 2011, has studied rainfall estimation from different satellite resources and found that all rainfall estimations displayed a high overestimation over dry regions and a underestimation over highland in Ethiopia. The reason behind the overestimation over dry land may be because there is a sub-cloud evaporation which is not taken into consideration. The underestimation over high land is because of warm orographic rain process. However, RFE 2.0 is more accurate than the precipitation data obtained from gauge measurements alone because it showed to reduce bias and random errors (FEWS NET rainfall estimation, 2011). This data has a bias of -0.15 mm/day and a good correlation of 0.501 with actual station rainfall amounts. I used 10-day (decadal) data with 0.1° spatial resolutions.

In addition, number of wet day's frequency data was obtained from CRU 3.1 with the same resolution as CRU rainfall data for the period 2000-2009. It was used to analyze the distribution of rainfall over the period of measurement time. Figure 6 shows the long-term monthly mean for period 2000-2010 of rainfall data and wet days in different locations Garoowe (northeast) and Jamame (southwest). The correlation between the rainfall and number of wet days' data was not strong in Garoowe as we can see in the figure 6 (top chart).

3.3. Land cover

MODIS land cover MCD12C1 was used to analyze the vegetation in the region of study and to provide help to understand and interpolate the results accurately. It corresponds for land cover in 2004 with the Climate Modeling Grid (CMG) format and a spatial resolution 0.05° (~5600 m) (LP DAAC, 2010a). It has three land cover schemes:

1. Land Cover Type 1: Defined by International Geosphere Biosphere Program (IGBP) global vegetation classification.
2. Land Cover Type 2: University of Maryland (UMD).
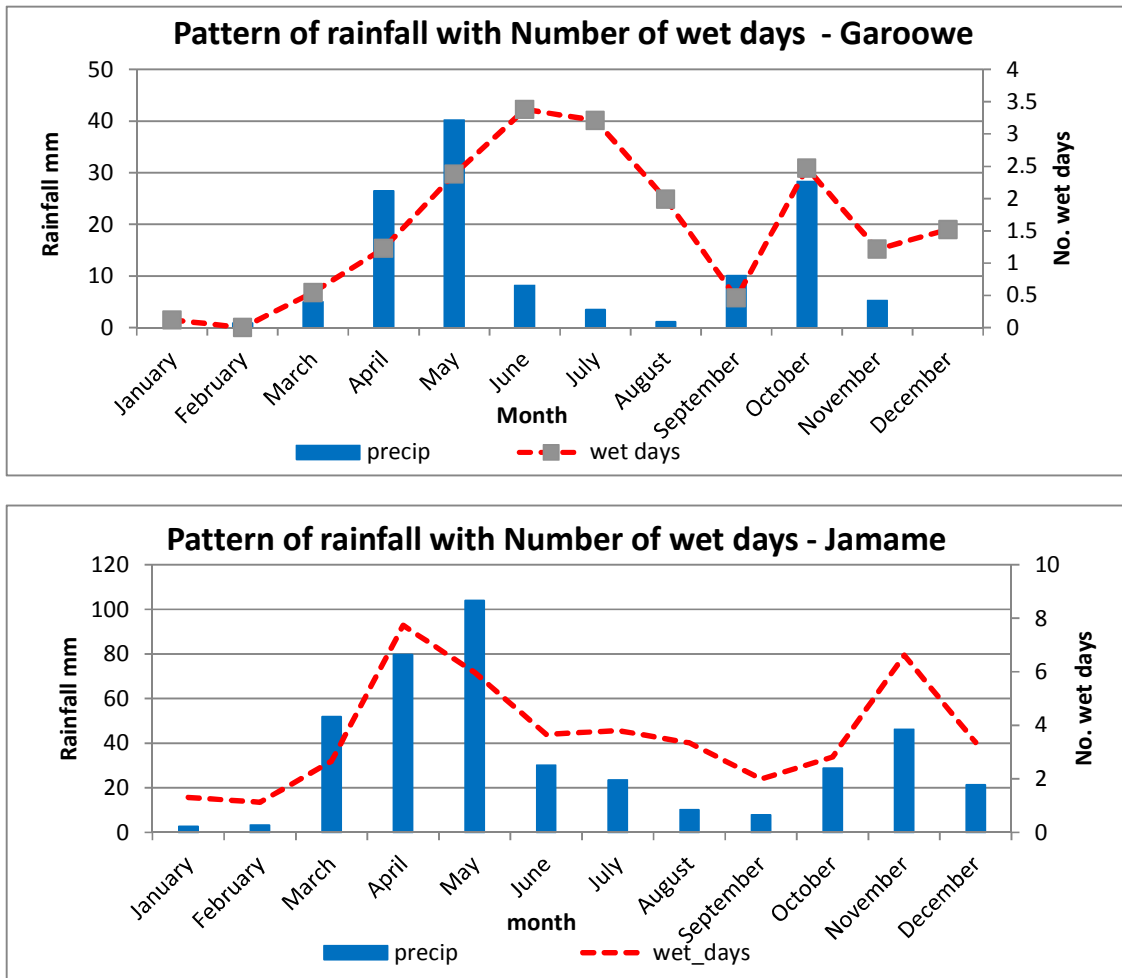
Figure 6 The pattern of precipitation in two locations in Somalia with Number of wet days. The data is a long-term monthly average for period 2000-2010 for precipitation and 2000-2009 for No. of wet days. Data source: CRU TS 3.1 and RFE 2.0

3. Land Cover Type 3: MODIS-derived LAI/fPAR.

In current study, land cover type 1 was used which has 17 land cover classes. Then these classes were combined and re-classed to seven land cover classes. Figure 4 shows the land cover classes in the region.

3.4. Population

This data was used to analyze the population density in the region and in the areas that were affected by drought in the period of study. It was downloaded from Center for International Earth Science Information Network (CIESIN) (2005), Gridded Population of the World (GPW) version 3, CIESIN, Columbia University. Population for Somalia was provided by Food Security Analysis Unit of Somalia, FSAU for the year 2000. Figure 7 shows the population density of the region.

3.5. Political boundaries vector map

This data is a vector map which was downloaded from International Livestock Research Institute (ILRI), 2007. It contains the political borders for Africa and Somalia districts.
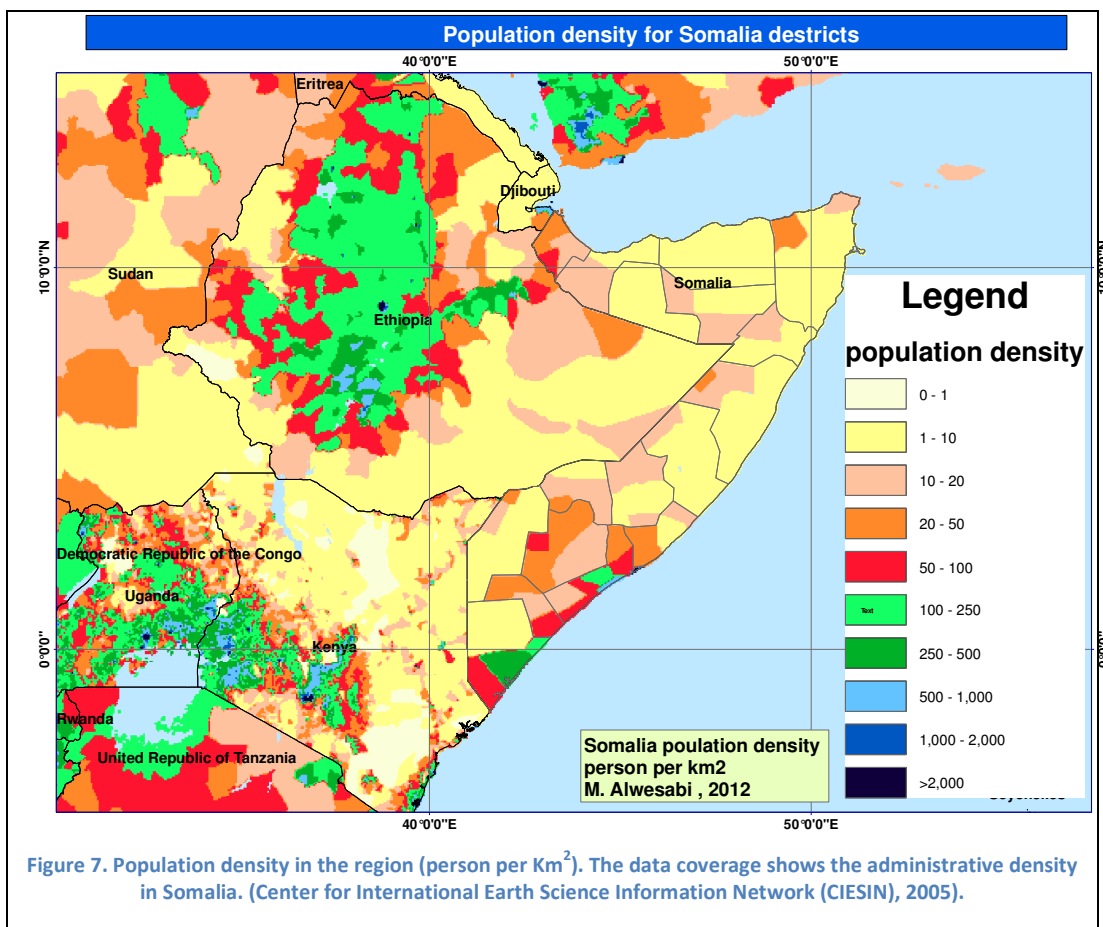
Figure 7. Population density in the region (person per Km^2). The data coverage shows the administrative density in Somalia. (Center for International Earth Science Information Network (CIESIN), 2005).

4. Methods

4.1. Pre-processing the data

4.1.1. NDVI

After downloading the data which has HDF-EOS format, MODIS Reprojection Tool was used to reproject the format to other geographical formats and it was used to resample the data using the nearest neighbor method. The tool also used to clip the region images with coordinates (30E–55E, -5S–15N) from the global images data. A software (Curve-5.exe) provided by Lars Eklundh was used to extract the data in pixel-base in specific locations.

Missing data

Missing data in NDVI dataset appears in the time series because of the effect of removing clouds and atmospheric aerosols, which reflect or absorb the reflectance from the ground. However, the missing data were replaced when it was necessary by using the following methods:

1. Single data: were replaced either by mean of 8-day value before and one after of time series or by the long-term mean for the same period when there was more than two missing values.
2. Monthly data: were replaced by the long-term mean of maximum data of the same.
3. Annually data: MCD43C4 data are 8-days images which mean 46 images annually then to make it easier for calculation in Matlab two empty images were created every year in April or May and October or November depends on the year if it is Leap or regular year.

4.1.2. Rainfall data

The CRU 3.1 data files are very large up to 2.5 gigabytes contains data for the period 1901-2009 and for the globe. In order to obtain the data for region (30E–55E, -5S–15N) and for the study period, a Matlab script developed by Lars Eklundh was used. The data is monthly values in grid with resolution of 0.5° and different interpolation methods were applied to the data for better estimation of rainfall (Mitchell, 2004). Some months such as January or December especially some dry months in dry zones in the data have same values which are the 1961-90 mean, as a result of a lack of stations data (features). These features are due to many reasons such as absent data in some areas in some developing countries, regions that receive only a small amount of rainfall, the rainfall in the form of localized shower or have a sparse network of rain gauges. These features are to make sure that the data is complete in space and time. However, these months usually are not growing months in Somalia and the effects of these features will not be significant.

4.1.3.2. RFE data:

RFE data are 10-day grid images with 0.1° spatial resolution. To make this data homogenous with CRU rainfall data, monthly, seasonal and annual means and sums were calculated for all the study locations.

4.1.3.3. Normal distribution:

NDVI monthly data showed a normal distribution while monthly rainfall data did not show a normal distribution with a strong positive skewness. Transformation methods are usually used to transform non-normal distribution data, to apply parametric test. Logarithmic and square root transformation methods were applied for rainfall data. Both methods did not provide good results even though logarithmic method was better. It might be because the raw data has a strong skewness influence by high records of rainfall in some rainy months and also by zeros in dry months.

Therefore, it was not possible to apply all parametric tests to rainfall data. Monthly rainfall data was only used in correlation and comparing with the normal average tests. All other parametric tests were performed only for NDVI. Another thing used to overcome this problem was to add the monthly data up to seasons which gave a better distribution.

4.1.3. Specific locations
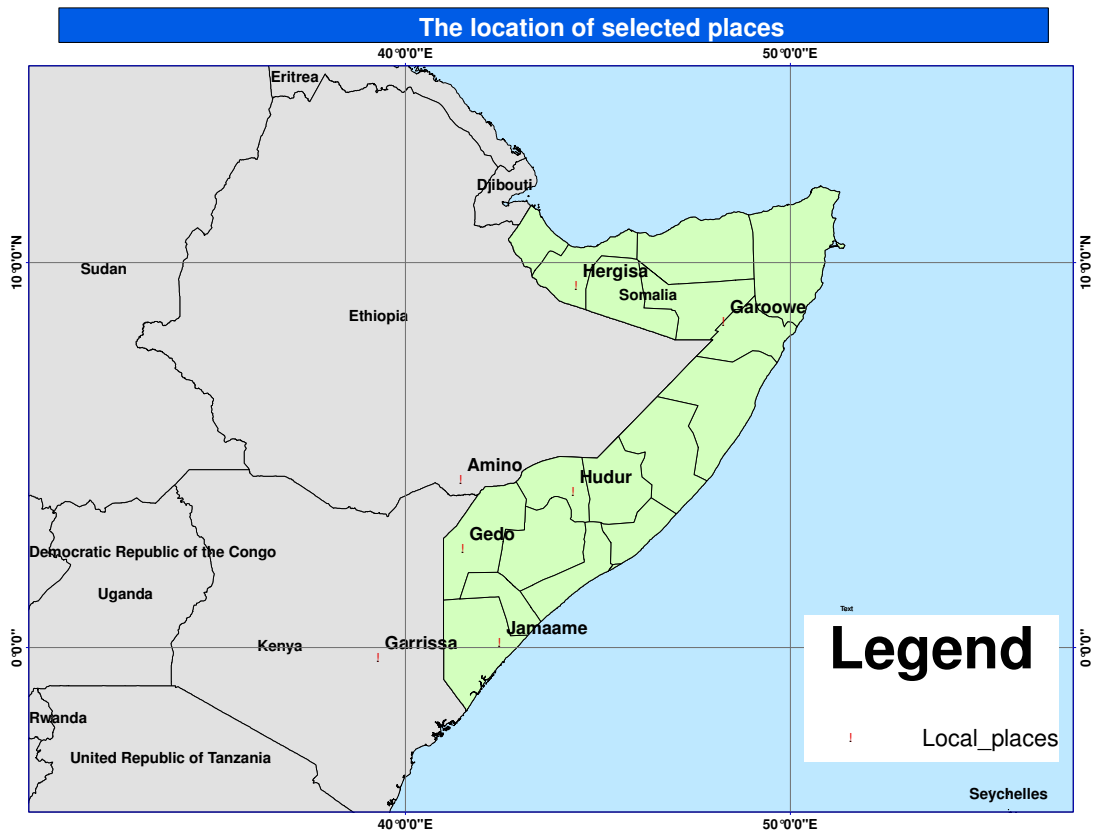
Figure 8 is a map of region with study locations in red circles. Country borders for Africa and administrative borders for Somalia provided by ILRI (2011).

To test the time series analysis and statistics locally, seven locations across Somalia and neighboring areas were selected, as shown in figure 8. Local levels represent different parts in the study area with different climatic zones from dry in the northeast to semi-dry zones in the south of Somalia. Specific locations are close to cities with distance from 20-50 km and were analyzed to show the overall change as a result of drought on regional

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vegetation ecosystem. They were selected as the typical areas to verify the connectivity of vegetation greenness and degree of drought. These places examined the specific temporal variation for the period 2000–2011 for NDVI and rainfall. Each location covers 1×1 pixel (pixel=5600 m in NDVI and 0.5 degree in rainfall data) to have a homogenous area and reduce the effects from surrounding pixels which might have different values such as that close to water bodies and big cities. Eklundh (1996) found that 1×1 pixel had the best correlation between rainfall and NDVI. Another criterion is that most of these regions were identified by the international aid organizations to be affected by the 2010 drought and classified as their situation crossed the famine threshold (FSNAU, 2011b). Two locations were selected outside of Somalia but close to the border in order to verify the difference between effects of drought from the effects of conflict.

4.1.4. TIMESAT software 3.0

TIMESAT is software developed by Lars Eklundh and Per Jönsson for analyzing time-series of satellite data (Jönsson and Eklundh, 2002; 2003; 2004). The TIMESAT software package uses filtering methods such as Savitzky-Golay, Gaussian and double logistic model functions to extract seasonality parameters. It has been used for different applications such as characterizing phenology, phenological changes and mapping high-latitude forest phenology. I used this software for two main purposes; first, was to apply filter for my data to smooth the NDVI curve. Second, was to analyze the seasonal pattern and parameters for the vegetation in the regions. Seasonality parameters are such as start and end of the season, length of the season, peak and amplitude of the season.

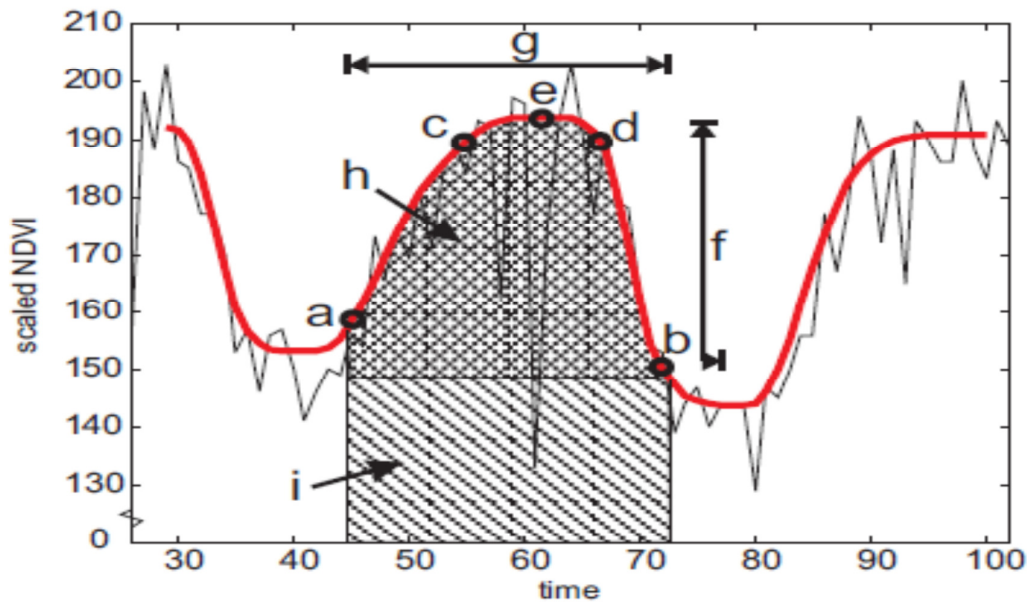

Figure 9 Resulting of TIMESAT fit to satellite data. Letters from a to h are seasonality parameters extracted by the software, black line is the raw data and red thick line is the fitted data (TIMESAT 3.0 manual, 2003).

Figure 9 shows an example of the software filter and the method to extract the seasonality parameters. Letters a-h are the seasonality parameters (a, b and e are start, end

and peak of the season respectively, c and d are 80% level of season, f and g are the length and amplitude of the season, h and i are the integral values of the season). Black and red lines are the raw and fitted data respectively.

MODIS Land cover image (figure 4) was used in this part to define the seasonality parameters for different land cover classes. Depending on Land cover data, it is divided to 6 sub- classes; forest, shrubland, savanna land, grassland, cropland and bare soil or desert. Each land cover class was inserted separately in TIMESAT to extract the seasonal parameters for each land cover.

4.2. Time series analysis

4.2.1. NDVI and rainfall relationship

In order to examine the strength of relationship between vegetation and rainfall or how much vegetation depends on rainfall, correlation coefficient and linear regression were calculated. Correlation were done temporally in different time scales (monthly, seasonal, and annual) and also spatially.

- Pearson's product moment correlation coefficient:

It was used to measure the strength of a relationship between two variables (rainfall and NDVI in this case). Pearson's product correlation (r) has a value between +1 to -1, close to 1 and -1 means that the correlation is perfectly matched positively and negatively, respectively (Wheater and Cook, 2003). The nearer r to zero, the less correlation there is between rainfall and NDVI.

Temporal correlations were calculated in month, season and year scale. Monthly correlation was calculated between the mean monthly NDVI and total monthly rainfall without time lag and with time lag of one month for NDVI. Annual correlations were calculated between the annual integral NDVI and annual rainfall. Also, spatial correlation was calculated between the average annual of rainfall with the average integrated annual of NDVI for all the study locations.

In order to reduce the effects of dry months on the monthly correlation, a correlation coefficient during the rainy months in the first and second seasons (April-June and October-November) was calculated. Seasonal correlation was calculated between monthly rainfall and monthly average of NDVI without time lag and with time lag a month. With time lag, the rainfall data for April-June and October- November was correlated with NDVI data for May-July and November-December. Rainy months were combined for each season separately for rainfall and then correlated with combined rainy seasons of NDVI. This procedure is also useful to reduce the effects of positive skewed in monthly rainfall data.

- Linear regression:

It is usually used to show the scatter plot between two variables: one depend on the other (rainfall and NDVI monthly data) and fit a line to the scatterplot (regression line) which describes the relationship of the two variables (Wheater and Cook, 2003). Rainfall data is as an independent variable in x axis and NDVI data is as a dependent variable in y axis. The straight line is described by the following equation:

$$y = a + bx \tag{2}$$

Where:

x and *y* are the variables;

a is the intercept of the line on the *y* axis (is the value of *y* when for example *x*=0);

b is the slope which shows the form of the relationship if it is positive or negative.

Excel software was used to calculate the linear regression between monthly rainfall and mean monthly NDVI, maximum monthly NDVI and integrated monthly NDVI. Raw NDVI data (before applying filtering methods) and filtered data obtained from TIMESAT software were used to in both correlation coefficient and linear regression.

The coefficient of determination (R^2) was calculated from both the correlation coefficient by squaring the value of r and linear regression It describes how much in common between the two variables; NDVI and rainfall (Wheater and Cook, 2003).

4.2.2. Detecting the drought onset and duration

4.2.2.1. Comparing with the long-term monthly average

Comparing monthly value of a variable in with its long-term monthly average can provide a good indicator for onset and duration of drought during the study period (Woo and Tarhule, 1994). Since the growth of vegetation is related to rainfall, rainfall data was plotted for the same years and using the same procedure as for NDVI to compare both results. For example for 2010 and 2011, NDVI mean monthly data and monthly rainfall was plotted against long term average 2000-2009. The reason why years 2010 and 2011 did not count in the long-term average is that both years have a severe drought and to include them might decrease the average, which would affect the detection of some years with normal variation as to be drought years.

4.2.2.2. z-test

Student test is used to compare the absolute difference between two means which provide an explained variation between two samples in time period (Wheater and Cook, 2003). The data was divided into two equal in size periods 2000-2005 and 2006-2011 and it is assumed that these two periods are independents from each other. Monthly NDVI data was used in this test. *Z-test* examines the null hypothesis: there is no significant difference between the two means of the two periods. Since the *z values* have no degree of freedom then if the value of *z-test* is equal or less than 1.96, it indicates a probability greater than or equal to *0.05* (no significant difference) and the null hypothesis is more likely to be true. Whereas, values greater than 2.576 indicate a probability less than *0.01* and then the alternative hypothesis is probably right, which says that there is a significant difference between the two means. Z-test has the following equation:

$$z = \frac{|\overline{x1} - \overline{x2}|}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{3}$$

Where:

$\overline{x1}$ and $\overline{x2}$ are the means of two periods, respectively;

s_1^2 and s_2^2 are the variance of the periods (square of standard deviation), respectively;

n_1 and n_2 are the sample sizes;

|| this symbol means the absolute values is taken (ignoring the sign).

4.2.2.3. Deviation from normal average

Another approach was to calculate the deviation from normal (Anomaly) by using the following equation:

$$\text{Deviation (t)} = x_{(t)} - \overline{x} \qquad (4)$$

Where:

x(t) is the value of NDVI at time t;

$\overline{x}$ is the long-term monthly mean of NDVI.

Long-term monthly average of the period 2000-2009 was subtracted from the mean monthly NDVI for every year in order to get the monthly anomaly which might give indication of drought periods. When the anomaly is positive, it is reveals above normal or no drought while negative value indicates below normal greenness or drought

Rainfall pattern varies spatially and so is the vegetation, then it is better to apply measures that can describe the intensity of drought. As it was mentioned previously, drought has three main components: onset, duration and intensity or severity. Therefore, drought should be defined by studying to all its three components.

4.2.2.4. Drought duration and its frequency

The relationship between drought duration and its frequency was tested by applying linear regression between drought duration and the time between drought periods in order of months in five locations. Slope and coefficient of determination were calculated from this test.

4.2.3. Detecting the drought intensity

4.2.3.1. Setting threshold

In order to analyze the intensity of drought, setting a threshold is one of the choices. Confidence interval is preferred to test the null hypothesis and quantify the magnitude of an observed effect (Jiroutek et al, 2003). Here, this test was used to test the null hypothesis that assumed there is no effect of decreasing rainfall on the NDVI. Setting a threshold can determine whether the impact of drought is crossed or not crossed this point. It is useful to compare the data with the normal condition with the average or the median with or without standard deviation (confidence interval). Bonacci (1993) defined this level as the mean with standard deviation multiplied with scaling factor. Two thresholds were set: 68% boundary for moderate drought impact and 95% boundary for severe drought impact. Then we can say there is no drought when monthly greenness value is within the 68% confidence boundary;

moderate drought when the value crosses this boundary; and drought becomes severe when the value crosses the 95% boundary.

Mean monthly data of NDVI and monthly rainfall were plotted with the 68% and 95% confidence interval of the mean to show the intensity of the drought in 2010 and 2011. 68% and 95% confidence interval is calculated from the following formula:

$$68\% \text{ confidence interval} = \mu \pm \sigma \tag{5}$$

$$95\% \text{ confidence interval} = \mu \pm (1.96 \times \sigma) \tag{6}$$

Where:

μ is the long-term mean 2000-2009;

σ is the standard deviation.

It should be mentioned that when choosing a mean for all of the years to set a threshold might be inappropriate for arid and semi-arid zones where the rainfall pattern is in distinct contrast from month to month. Setting one mean for all months will result in that all dry months are considered as drought months while rainy months as the opposite. Therefore, it is better to set a threshold for every month separately depending on its long-term mean.

4.2.3.2. Quantify the change

The percentage of change was used to quantify the change in season for both NDVI and rainfall during the study period. The percentage of change was calculated using the long-term seasonal average for period 2000-2009 for NDVI and rainfall. The following equation was used:

$$\text{The changes } \%(t) = \frac{(x_{(t)} - \bar{x})}{\bar{x}} \times 100 \tag{7}$$

Where

x is the seasonal mean NDVI or total rainfall;

$\bar{x}$ is the long-term seasonal average.

The mean seasonal of NDVI for all seasons was calculated first then the long-term seasonal average was subtracted from every seasonal mean and divided by the long-term seasonal average. There were 23 seasons for NDVI and 24 seasons for rainfall depending on the availability on the data on the last season of 2011 which is not available for NDVI on the time of analysis.

Quantify the change in a large-scale.

Percent of change for the whole region was calculated drought years in the study period to show the impact of drought in these years. The annual maximum for NDVI was calculated for every year for all years. The long-term average of the annual maximum for the period 2000-2009 was taken and then subtracted from the 2010 and 2011 maximum and multiplied with 100. The resulted image was reclassed to show the percentage of the changes in the categories.

Depending on the value of the change, degree of drought in the study region can be divided into five levels. Values equal or greater than zero indicate no drought; values between 0-10 percent less than normal indicate mild drought; values between 10-20 percent indicate moderate drought; values between 20-30 percent indicate severe drought and values greater than 30 percent indicate extreme drought.

5. Results

5.1. NDVI and rainfall correlation

4.1.1. Monthly correlation and linear regression

Statistics from pixel-by-pixel monthly rainfall and the mean monthly NDVI correlation coefficient between rainfall and NDVI data are shown in table 2. The correlation was calculated for the same time period between rainfall and NDVI without time lag and also with time lag 1 month for NDVI. Time lag means that NDVI data for the month (e. g. February) is correlated with the data rainfall for month before (e.g. for January). Results indicated two things: first, almost all of the study places were found to have a significant correlation at 95% (*df<0.05*) and 99% (*df<0.05*) with and without time lag. In Garoowe (Northeast) the correlation was not significant with time lag even though it was significant at 95% and 99% without time lag. Second, the correlations were positive in all locations without and with time lag.

Table 2 *Monthly correlation coefficient for mean NDVI and monthly rainfall in study places. Values in bold line indicate a significant correlation in 95% confidence (p=0.05). Values that are bold and with underline indicate a significant correlation at 99% confidence (p=0.01) at df=n-2. R^2 and slope were calculated from linear regression*

Area	Monthly -lag0	Monthly -lag1	R^2- lag1	Slope -lag1
Hergisa	**0.42**	**0.52**	**0.2671**	0.0006
Garoowe	0.30	0.18	0.0338	0.0003
Hudur	**0.45**	**0.57**	**0.3238**	0.001
Gedo	**0.57**	**0.59**	**0.347**	0.0012
Jamaame	0.23	**0.42**	0.1747	0.001
Amino	**0.44**	**0.54**	**0.2885**	0.0008
Garrissa	0.39	**0.51**	0.2578	0.0007
	df=138	*df=137*		

Generally, the correlation coefficient with time lag one month for NDVI was higher than without time lag (0.48 in comparison with 0.40, repectively). Even though, the correlation was significant in most of the locations, coefficient of determination was only significant in three locations with 0.35, 0.32 and 0.29 in Gedo, Hudur and Amino, respectively. This means that in Gedo 35% of the variation in NDVI was explained by rainfall. In Garissa and Hergisa, it was only significant in 95% confidence with R^2 value of 0.26 and 0.27 while in Garoowe R^2 was almost zero. All the regions were shown a positive slope between the rainfall and NDVI especially in the southwest Somalia (e.g. Jamame, Hudur and Gedo). Correlation between rainfall and NDVI showed to be higher between mean monthly NDVI with total monthly rainfall than the correlation between total or maximum monthly NDVI with total monthly rainfall.

5.1.2. Seasonal and annual correlation

Result of correlation coefficient is given in table 3. Significantly, two important results are indicated; first is that second rainy season has a better correlation between rainfall and

NDVI than the first season without time lag and with time lag except in Hergisa in northwest where correlation was higher in the first rainy season. Second is that the correlation coefficient without time lag is higher than with time lag in most of the locations except in Jmame and Garrissa in second rainy season. Annual correlation is the correlation between the annual mean rainfall and the annual mean NDVI. Results indicated that only a significant correlation in Hergisa whilst no correlation or even negative in Jamame.

Table 3 Correlation coefficient for NDVI and rainfall during the rainy months. Also, annual correlation between annual mean NDVI and rainfall. Values in bold line indicate a significant correlation in 95% confidence (p=0.05). Values in bold and underline show a significant correlation at 99% confidence interval (p=0.01). Rainy seasons are April, May, June for first season, October and November for second season. Time lag is one month for NDVI.

Location	Rainy months 1_lag0	Rainy months 1_lag1	Rainy months 2_lag0	Rainy months 2_lag1	Annual
Hergisa	**0.9138**	**0.8361**	0.2272	0.0114	**0.67**
Garoowe	**-0.4168**	**-0.3772**	0.2014	0.1835	0.27
Hudur	0.0741	-0.2601	**0.5204**	**0.4296**	0.14
Gedo	**0.5481**	**0.3752**	**0.4257**	0.3993	-0.31
Jamaam	**0.3552**	0.0837	0.0942	**0.5061**	-0.10
Amino	-0.3137	-0.1621	**0.5872**	**0.5736**	0.38
Garrissa	-0.29	-0.27	**0.4433**	**0.6309**	0.39
df=n-2	*df=33*	*df=33*	*df=22*	*df=22*	*df=9*

Coefficient of determination (R^2) was compared in different time scales (monthly, seasonal, annual) as in the figure 10. Boxplot in number one in the figure is the value of R^2 for the correlation between monthly rainfall with mean monthly NDVI with time lag one month; two is for mean rainfall with mean NDVI in rainy months; and three is for annual mean rainfall with annual mean NDVI. Red line in box plot is the median and upper and lower quartiles are the 75%, 25% of the median. Whiskers are the maxima and minima of the coefficient of determination. Red pluses considers being as outliers. It is clear that monthly coefficient of determination with median of 0.27 is higher than seasonal and annual R^2 with almost zeros or even negative.

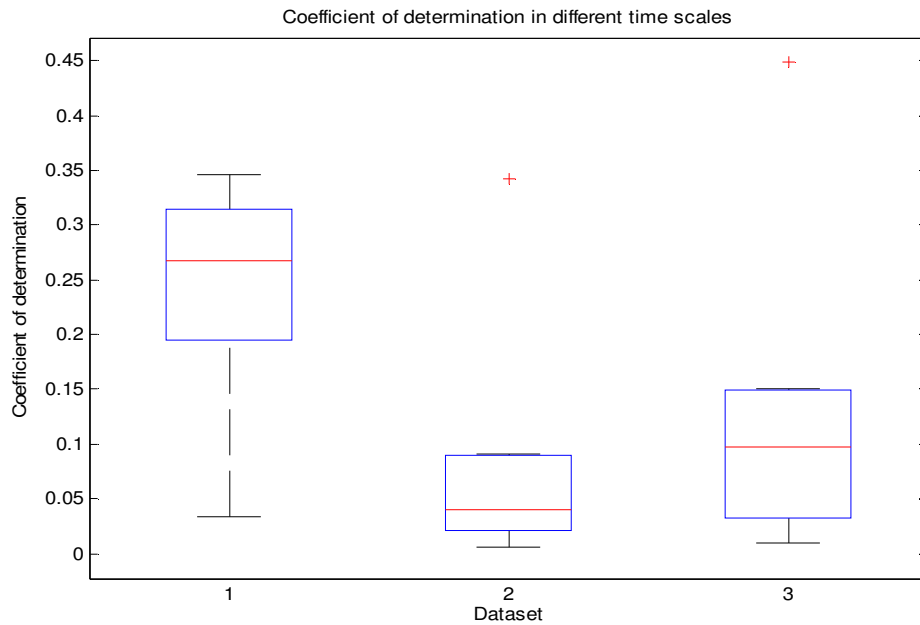Coefficient of determination in different time scales

Figure 10 Boxplot of mean coefficient of determination for all locations of relationship between rainfall and NDVI at different time scales. Boxplot shows median (red line), 25% and 75% are the quartiles; whiskers are the minima and maxima and red plus are outliers. Boxplot 1 is for monthly R^2 and two is for seasonal R^2 and three is for the annual of Coefficient of determination.
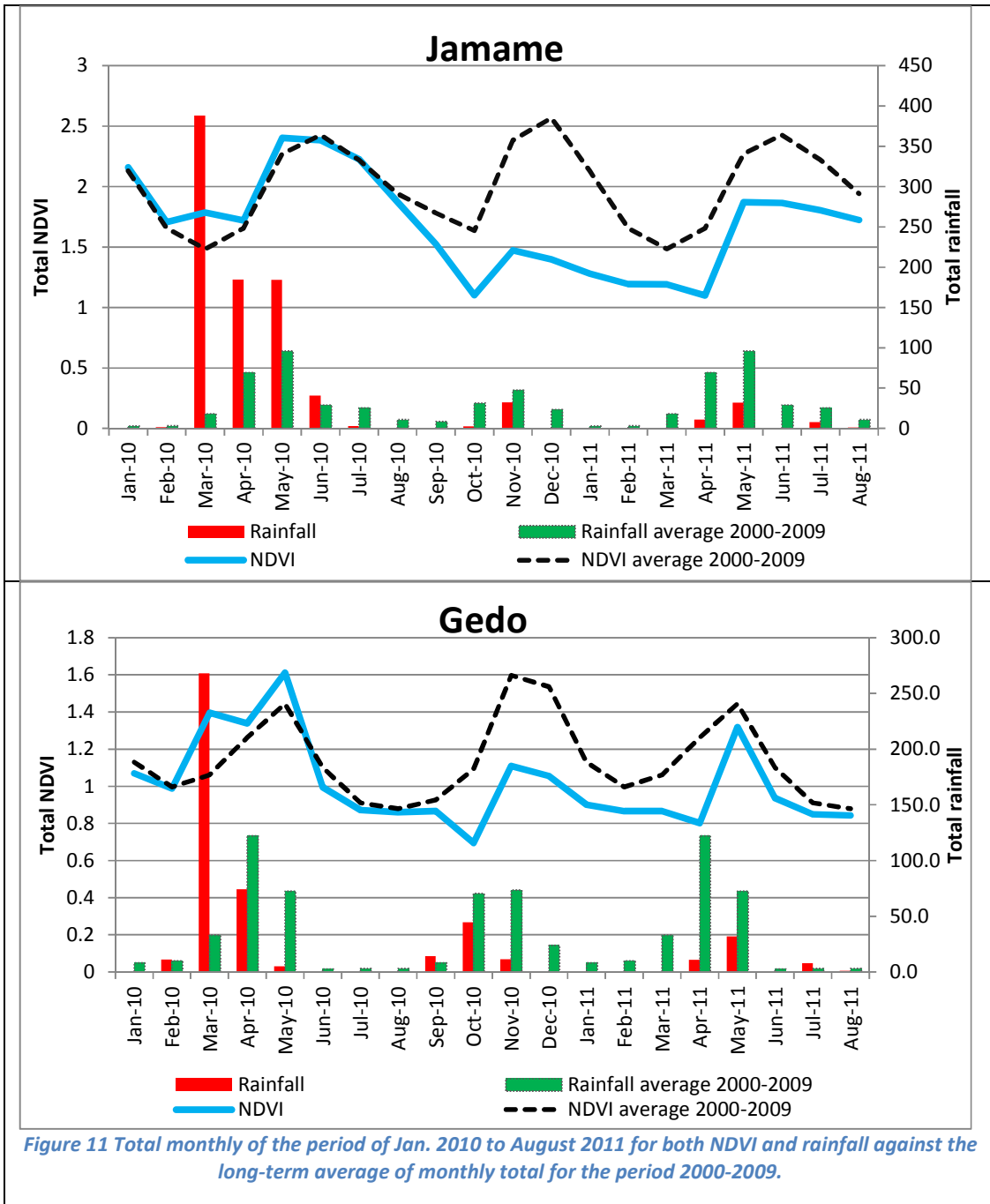
5.2. Detecting the drought onset and duration

To detect the drought in Somalia and adjacent regions three methods were used: the first one is to plot the monthly average for each year during the study period against the long-term average of the period 2000-09 for both NDVI and rainfall data. Second is *z-test* (student test) that was used to analyze the difference between two periods in the data. The last one is to plot the anomaly of NDVI.

5.2.1. Comparing with normal conditions

The NDVI and rainfall data for each year for period 2000-2011 plotted against the long-term monthly average (2000-2009). Figure 11 shows the NDVI and rainfall data in two locations as an example for 2010-2011 drought years against the normal average. In 2010, there was above normal NDVI and rainfall in the first main season especially in March and below average in the second short season and this reduction in NDVI and rainfall continued in the first season of 2011. In Jamame, drought started in October while in Gedo drought started in June. Also, there is a clear response of NDVI toward changes in rainfall with increasing and with decreasing clearer but with time lag.

This test were done for all years and table 4 is summarized these results. Numbers in the table indicate above or below long-term seasonal average greenness where minus one indicates below average while plus one indicates above average and cell without numbers indicates equal or close to average. These results indicated that NDVI varied temporally and spatially. Above and below normal average in first and second season followed regular pattern in most the study locations in many years. Most regions showed similar results from different years such as years 2001, 2005, 2006, 2007 and 2011. There are some regions which are

exposed to the below average or drought more than others and according to this test Amino in south of Ethiopia is the most locations exposed to drought during the study period while

Figure 11 Total monthly of the period of Jan. 2010 to August 2011 for both NDVI and rainfall against the long-term average of monthly total for the period 2000-2009.

Hergisa was the lowest one. Two important points can drown from the results in the table: first, is drought often starts in the second rainy season and continues to the first rainy season in the nest year, and second point is that drought rarely comes in two seasons in the same year except in 2000.

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Table 4. Results of the test in section 5.2.1. Plus one indicates above average NDVI and minus one indicates below average NDVI while without number is equal or close to the average.

year	season	Hergisa	Garoowe	Hudur	Jamame	Gedo	Amino	Garrisa
	first season	-1	1	1	-1	-1	1	-1
2000	second s.		1	-1	-1	-1	-1	-1
	first season				1		-1	
2001	second s.			-1		-1	-1	1
	first season	1	1	-1				1
2002	second s.			1	1		1	
	first season		-1	1	1		1	1
2003	second s.		-1	-1			-1	1
	first season	-1	-1		1		-1	
2004	second s.	-1	1	1	1	1	1	1
	first season	1	1	1			1	
2005	second s.	1	1	-1	-1	-1	-1	-1
	first season		1					-1
2006	second s.	1	1	1	1	1	1	1
	first season	1		1	1	1	1	1
2007	second s.	1	-1	1		1	1	1
	first season		-1	-1	1	1	-1	
2008	second s.			1	-1	-1	1	-1
	first season	-1	-1	-1	-1	-1	-1	
2009	second s.	-1		1	1	1	-1	1
	first season	1	1	1		1	-1	1
2010	second s.		-1	-1	-1	-1	-1	-1
2011	first season		-1	-1	-1	-1	-1	-1

5.2.2. Z-test

A z-test was calculated to show the differences between means of two periods, the first one 2000-2005 and the second 2006-2011 for NDVI data (table 5). Values in bold line and underline indicate a significant difference at 95% and 99% (p=0.05, 001) respectively. Results from this test show that there were significant differences between the two periods in three places at 99% confidence interval (Hergisa, Garoowe, and Jamame) while it was significant at 95% confidence in Amino and no significant difference at three other locations (Gedo. Hudur, and Garrissa).

5.2.3. Deviation from normal average

Calculating the deviation from normal average provides a clear vision of drought onset and duration during the study period. This test was performed for all drought years which are 2000, 2003, 2005, 2008 and 2010-2011. Figure 12 shows the monthly anomalies of NDVI in 2010 and the first 8 month of 2011 in the study places.

Results of NDVI anomaly show that in 2010 (red line with circles) there was above normal greenness in the first rainy season and below normal in the second rainy season in almost all the regions except in Hergisa (northwest). In 2011, the first rainy season showed below normal greenness (green line with square boxes) in all regions. The lowest anomalies showed in October-November 2010 in most of the locations and in April 2011. However, there was a recovery or increase of greenness in the end of 2011 first season in most of the location except in Jamame. According to this test, the drought started in October 2010 (second rainy season) in all locations (except in Hergisa) and continued until August 2011.

Table 5. Results from z-test for NDVI between two periods in the data: 2000-2005 and 2006-2011. Values in bold line indicate a significant difference at 95% confidence interval (p=0.05). Values that are bold with underline show a significant difference at 99% (p=0.01).

Location	NDVI (2000-11)
Hergisa	**3.9909**
Garoowe	**3.2449**
Gedo	1.5979
Jamame	**4.8147**
Huddur	1.1876
Amino	**2.3417**
Garrissa	1.8516
$df=n_1+n_2-2$	70
t values at p=0.05	1.98
t values at p=0.01	2.626

5.3.4. Correlation between the duration of drought and its frequency.

A linear regression between the duration of below average greenness with its frequency showed that the relationship between them during the period of study (12 years) was negative in all the locations. Frequency of dry spells decreased with increasing of their duration. Values of deviation not less than 10% of negative change were used in this regression. Table 7 shows the slope and coefficient of determination for this regression in 5 locations. The mean coefficient of determination of the locations results was 0.39 and mean slope was -0.23.

Table 6. Slope and coefficient of determination of the linear regression between the duration of below normal greenness with its frequency

	slope	R2
Amino	-0.14	0.42
Garo	-0.31	0.28
Gedo	-0.12	0.27
Jama	-0.32	0.39
Hud	-0.26	0.6

5.3. Detecting drought intensity and area affected

5.3.1. Setting threshold

As it mentioned in the section 4.2.3.1, 68% threshold suggests no drought if the monthly value is within this threshold and severe drought if it is below this threshold and extreme drought if it is below the 95% threshold. Figure 13 shows the result for NDVI for 2010 and 2011 years where cyan and green shaded areas are 68% and 95% confidence interval -inside and outside- respectively; and blue with squares, red with circle and dashed lines are the NDVI mean monthly data for 2010, 2011 and long-term monthly mean of the period 2000-2009, respectively.

Results indicated that there was no drought in first season in 2010 and a severe drought in second season of 2010 and first season of 2011 in most of the study locations except in Hergisa and Jamame. In Hergisa, there was not any drought in this period whilst in Jamame there was an extreme drought from November in 2010 to February in 2011. According to this test's results, the severe drought continued to March in Garoowe; to April in Amino and Hudur and to June in Gedo, Jamame and Garissa.
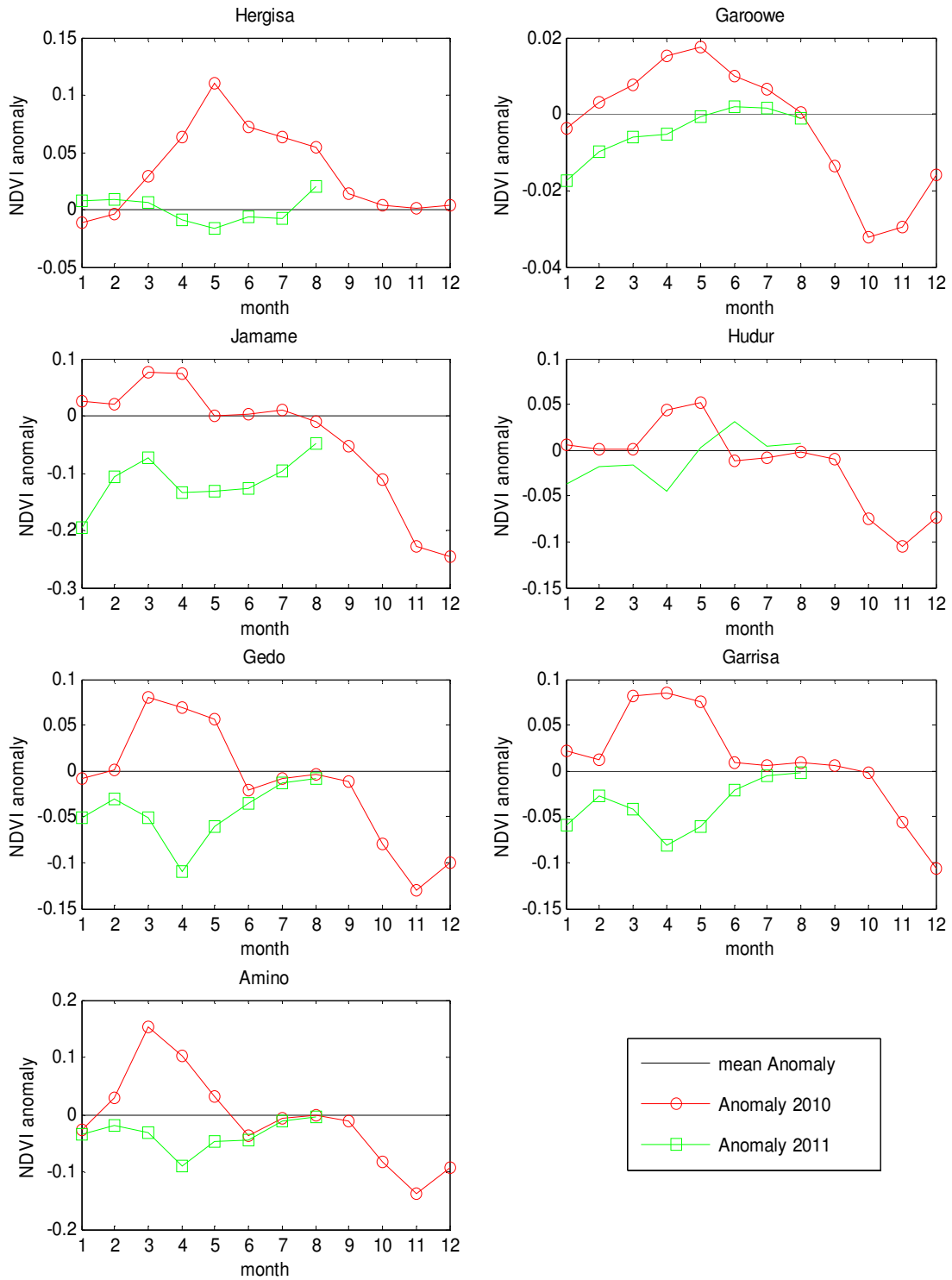
NDVI anomaly for 2010 and 2011

Figure 12. Monthly anomalies of 2010 and first eight months of 2011 plotted for the study locations. Data for 2010 in red lines with circles and for 2011 in green lines with boxes.

NDVI pattern in 2010-2011 with the threshold of 68% and 95% confidence interval
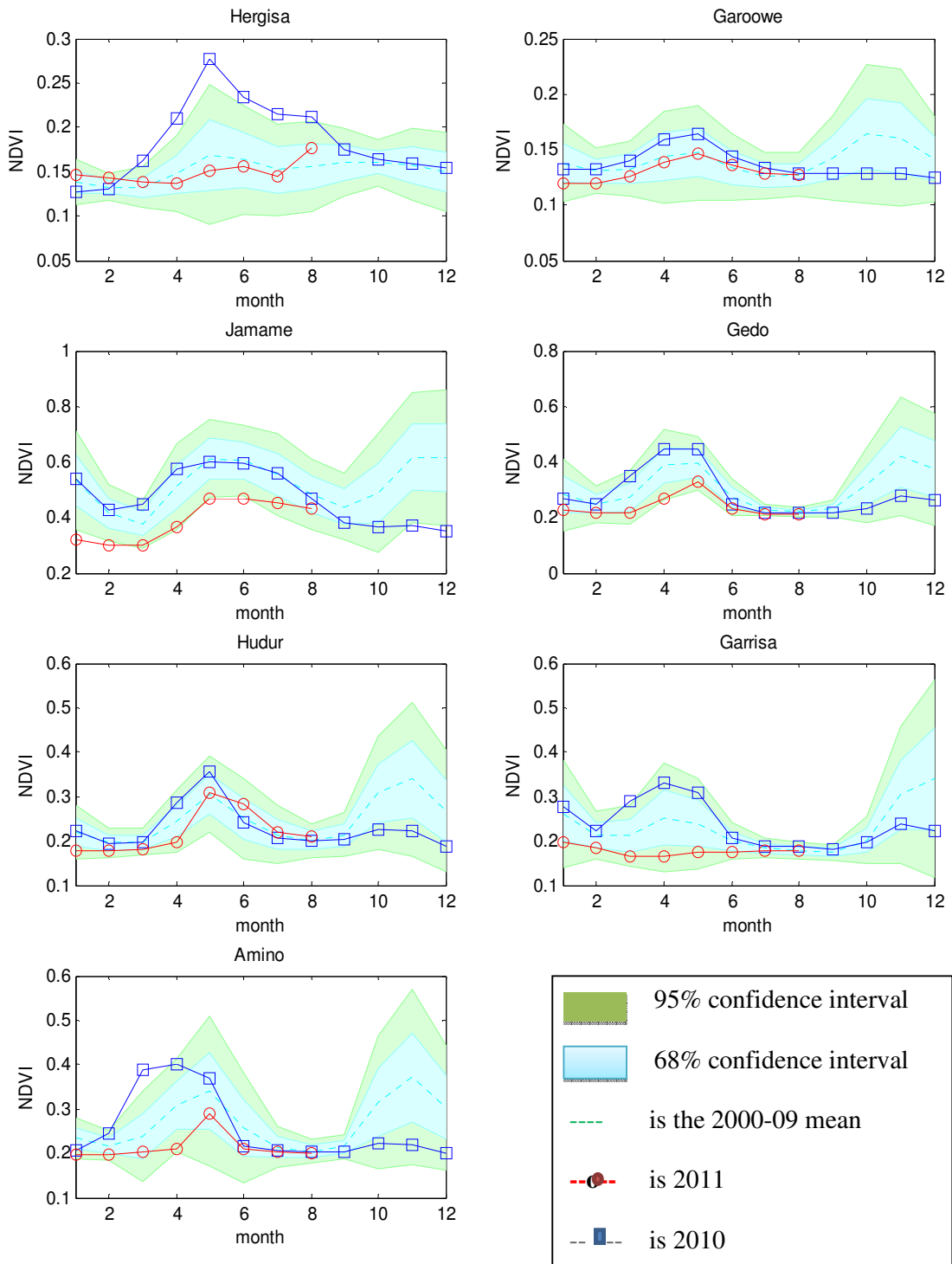
Figure 13 mean monthly of NDVI for 2010 and first eight months of 2011 with the 68% and 95% confidence interval. The inside shaded area is the 68% confidence interval while the outside shaded area for 95% boundary. Lines with square, circles and dashed line are monthly data for 2010, 2011 and long-term average.

5.3.2. Percent of change

Seasonal mean of NDVI and rainfall were used to quantify the change of NDVI and rainfall in comparison to the long-term seasonal mean of 2000-2009. Graphs in figure 14 show the results from this test while tables in appendix 3 summarized the results from both NDVI and rainfall data. Depending on the degree of change, a suggestion for classification of drought impact is found in table 6. In the following paragraphs, more descriptions about the percentage of change for each location is given:

Hergisa: located in a semi-dry zone in the northwest where rainfall pattern showed that the two seasons were not clearly separated or there were only one long season in some years. Changes in rainfall showed that this region receives a different amount of rainfall every season. This area experienced drought in some seasons like in 2006, 2008 and 2009,

Table 7 degree of drought depends on the percent of change for NDVI only

Value	Degree of drought
>= 0%	No drought
-1% to -10%	Mild
-11% to -20%	Moderate
-20% to -30%	Severe
< -30%	Extreme

when rainfall decrease to 68% less than normal, while in years 2004, 2010 and 2011, the region received a significant amount of rainfall. NDVI did not show any a severe or an extreme drought but there was moderate drought in 2009. In 2010 greenness increased by 58% when the there was a significant amount of rainfall up to 214% more than the average in the first season.

Garoowe: located in the northeast in the dry zone. Results from NDVI changes indicated a severe drought in second seasons of 2003 and 2010 with negative change 30% and 22%, respectively. Changes in rainfall proved NDVI results in 2010 with negative change 50%. In 2011, there was a negative change in rainfall with -48% but NDVI showed no change.

Hudur: located in the semi-arid zone in southwest. Rainfall appeared to be less changeable than NDVI except in the last three seasons. NDVI indicated an extreme drought in second seasons of 2003 and 2010 with negative change 40% and 35%, respectively. Rainfall indicated drought in second seasons of 2010 and first season of 2011 with negative change 70% and 60%, respectively.

Gedo: located in the semi-arid zone in southwest. NDVI indicated an extreme drought in second seasons of 2001, 2005 and 2010 with negative change 30%, 41% and 33%, respectively. Changes in rainfall indicate the results of NDVI changes in 2010 and 2011.

Jamame: located in the semi-arid zone in the southwest and it received the highest amount of rainfall among all the locations. Rainfall fluctuated from year to year but this did reflect in NDVI pattern which might be due to the type of vegetation, which tends to be woody. Results of NDVI indicated a extreme drought in second season of 2010 and severe drought in first season of 2011. The highest record of negative change in rainfall was in second season of 2010 and first season of 2011 with -55% to 78%, respectively.

Garrisa: located in the east of Kenya close to Somalia's border. Results of NDVI changes indicated that there was a severe drought records in second season of 2000, 2005 and first

season of 2011. Rainfall data changes indicated the result of NDVI in 2005, 2010 and 2011 with negative change about 18%, 68% and 91%, respectively.

Amino: located in south of Ethiopia close to the Somalian border with semi-arid climate. NDVI results indicated that there was an extreme drought in second season of 2005 and 2010 and a severe drought in first season of 2011 with 34%, 38% and 21% below the average, respectively. Rainfall results proved the result of NDVI in 2010 and 2011 with negative change of 98% and 88%, respectively.

To conclude, there were extreme drought seasons in Hudur, Gedo, Jamame, and Amino and severe drought in Garoowe and Garrissa while there was no indication of drought in Hergisa. Also, there was extreme drought in Hudur in 2003, in Gedo in 2001 and 2005 and in Amino in 2005. Result from rainfall change indicated the extreme drought in the last two years. In second season of 2011 there was a significant amount of rainfall received in almost all the areas except in Garoowe which means recovering from the extreme drought of 2010-2011.
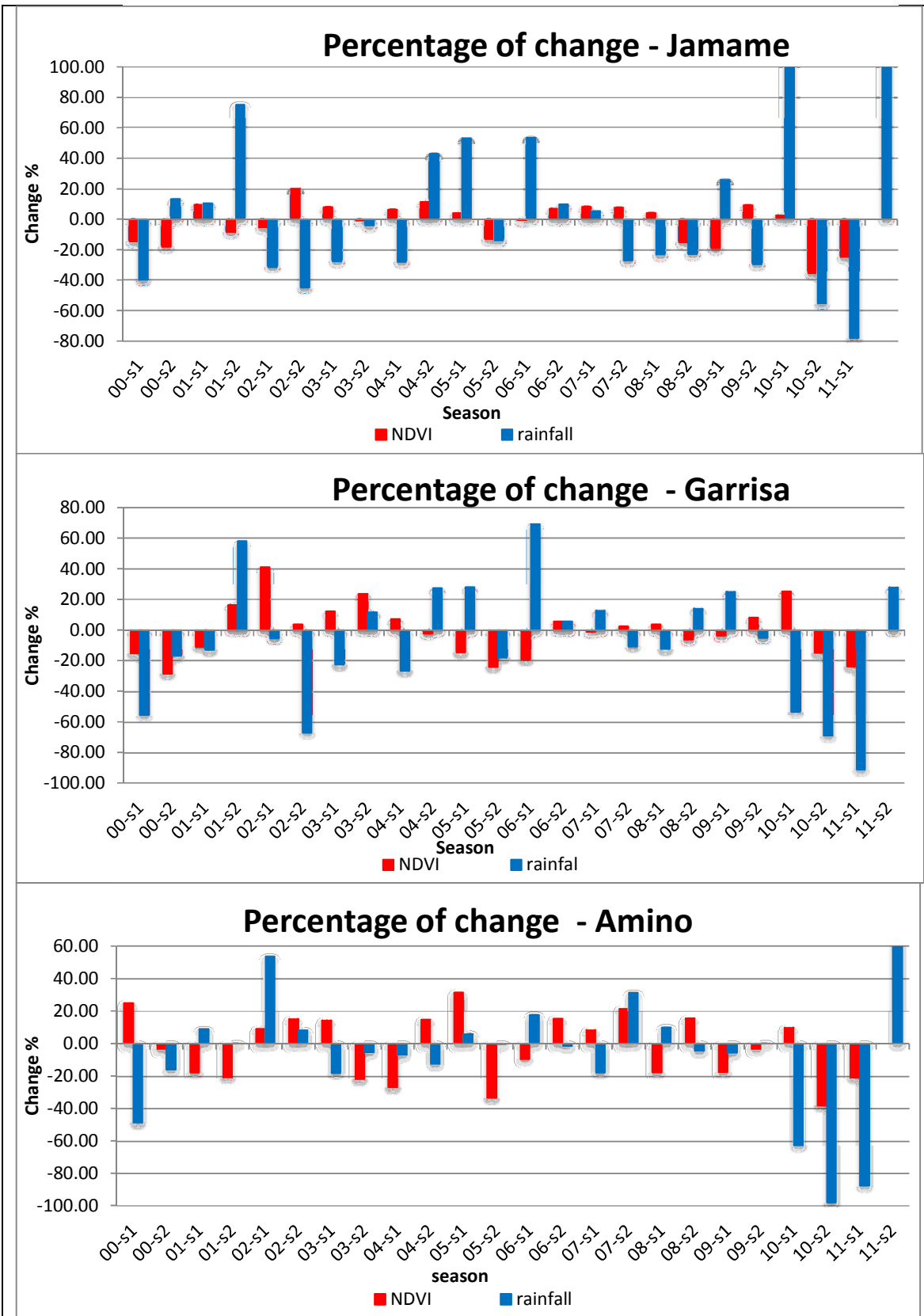
Percentage of change - Hudur

Percentage of change - Gedo
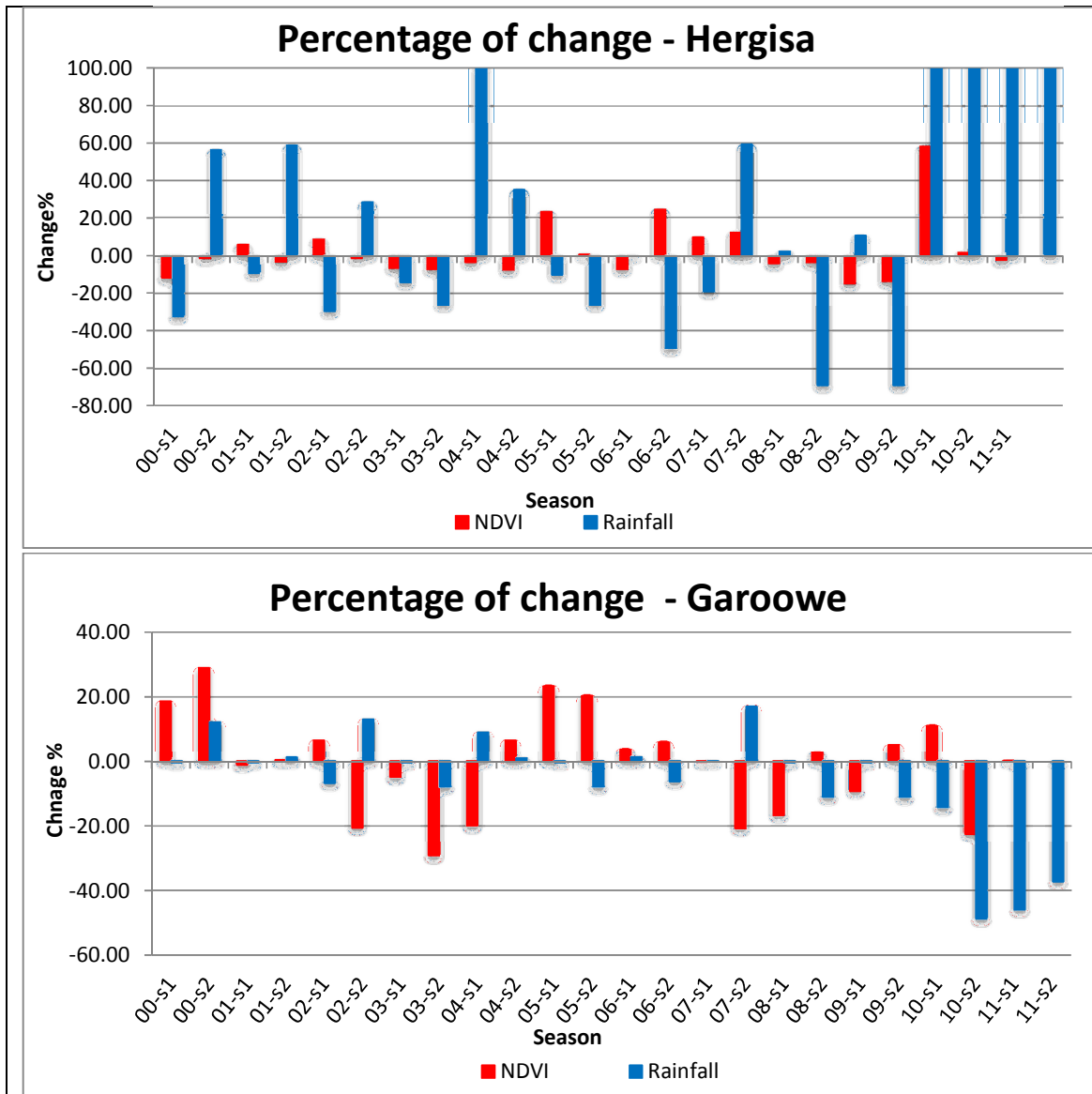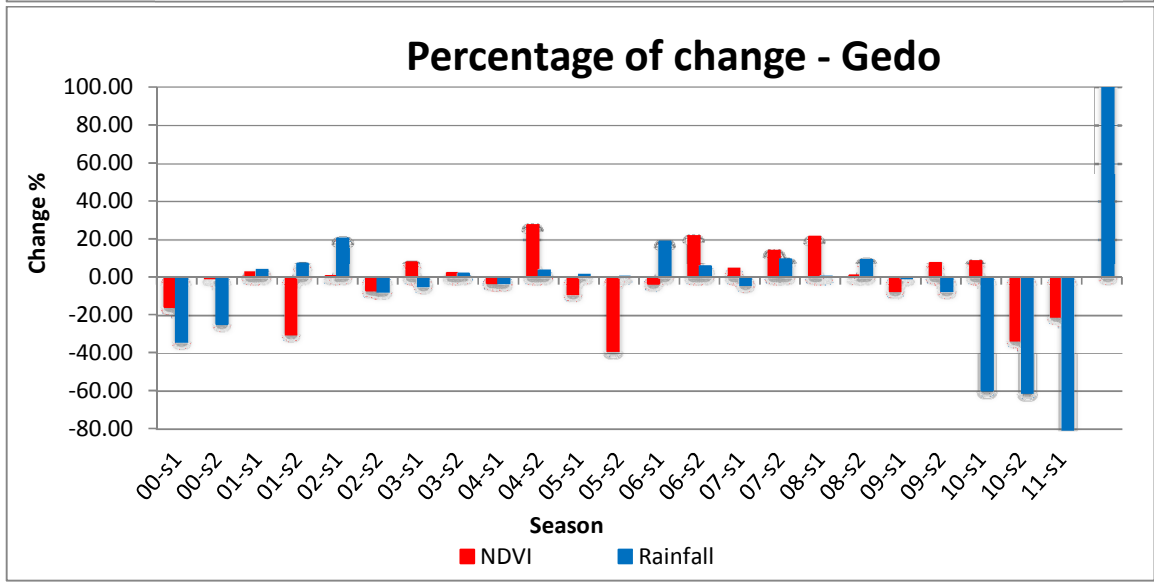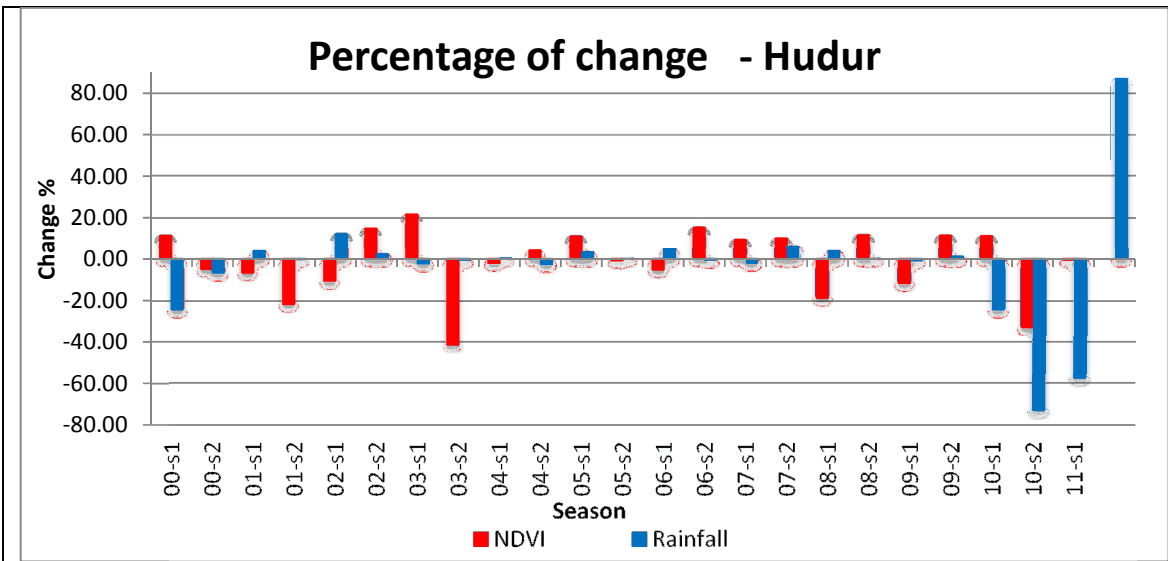
Figure 14 Seasonal percentage of change over the period 2000-2011 of NDVI and precipitation in the study areas.

5.3.3. The percentage of change for regional-scale

In the previous results described in section (5.3.2), the quantified change in the study places may not provide a good overview for the drought impacts. A calculation of the percent change was thus calculated for the whole regions by pixel by pixel calculation using the annual maximum NDVI. Figure 15 shows the percent change in the above image for 2010 and below one for 2011.

In 2010, there was mild to moderate drought impact (10% to 20%) in the second season of 2010 according to the map in figure 15. Most of this impact appeared in the central and northeast part of Somalia, east of Kenya and south of Ethiopia. The other part of Somalia and the region showed no change in NDVI or was above the average such as in northwest of Somalia; east and some areas of south of Ethiopia and west and northwest of Kenya.

In 2011, the impact was clear in southwest of Somalia in the east and northeast of Kenya (figure 15). The impacts of drought was a mild change (-10%) in some part of the central region in Somalia to moderate (-20%) in the northeast and the central part of Somalia, and in the south of Kenya and Ethiopia. In the southwest of Somalia as well as the east and the northeast, the impacts of the drought ranged from severe to extreme and reached values less than 50% in the northeast of Kenya (near to Turkana Lake) and in small spots in the southwest of Somalia. There was also an increase in NDVI with 20-40% in some areas in the northwest of Somalia and the east of Ethiopia.
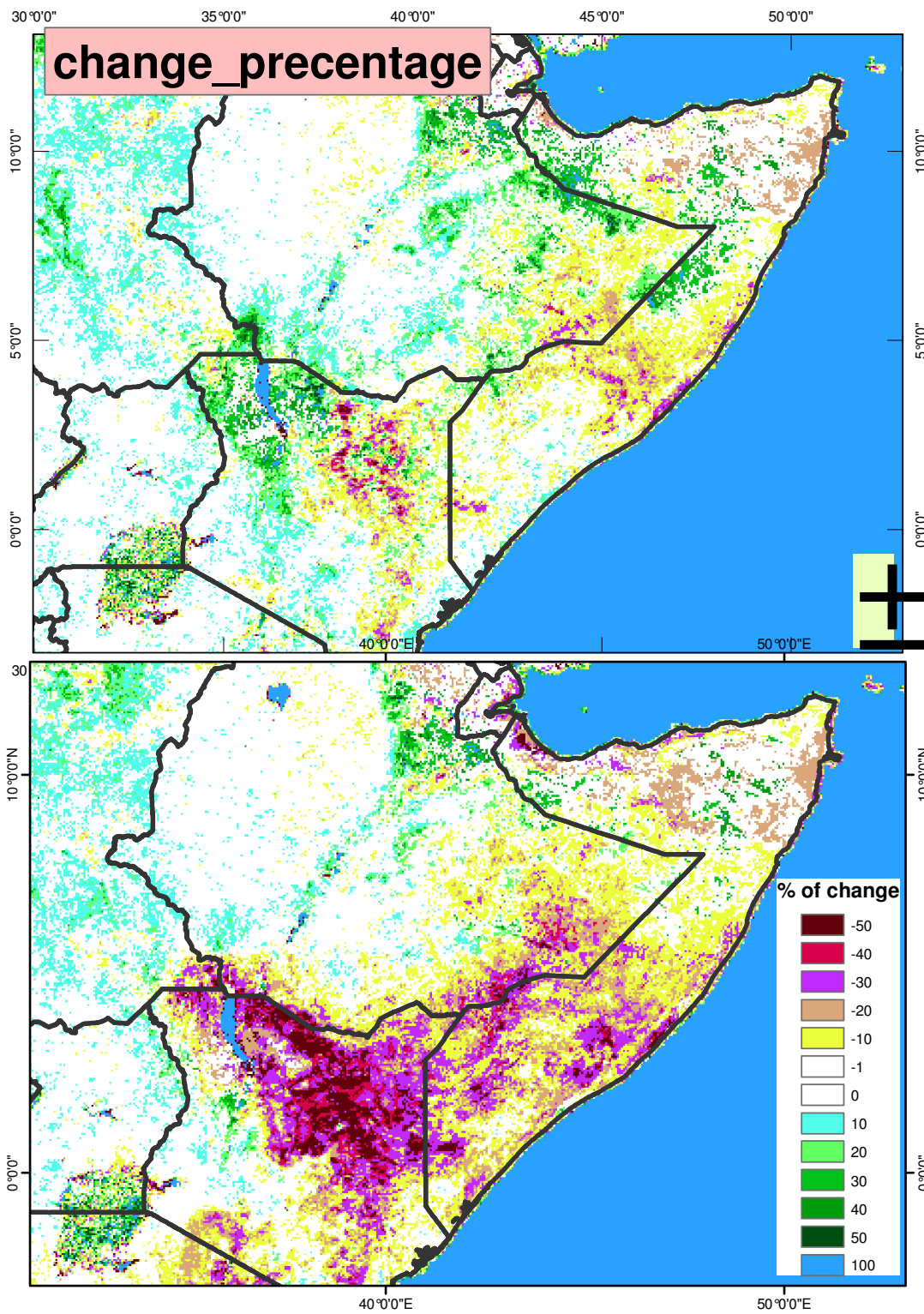
Figure 15 Percentage of change in the region. Top image is for 2010 and below is for 2011.

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6. Discussion

6.1. Detecting the drought intensity

The results of the two tests indicated that the drought of 2010-2011 was the most extreme drought during the study period. The characteristics of this drought are its extreme intensity from -30% to -50% negative changes and its long duration (more than 12 months in most of the region locations). The drought intensity for the year 2011 shown in figure 15 indicated that most parts of southern Somalia and eastern and northeastern Kenya were affected by extreme drought, where the negative change in greenness reached up to -50%, especially close to the lake of Turkana. Similar results were mentioned in report of Food Security and Nutrition Analysis Unit on 13 September, 2011 (FSNAU, 2011b) which reported that less than 10% of normal average rainfall received in that part of Kenya. A comparison between drought intensity for different drought years for different locations is shown in the figure 16. Values in the figure are the mean of a second season and a first season in the following year (e.g. mean of the second season of 2010 and the first season of 2011). The intensity of drought in 2010-2011 was on its highest in three locations (Jamame, Gedo and Amino); in 2003 in Garoowe and Hudur; and in 2005 in Garrissa. These results are similar to the FEWS NET reports in July 20, 2011 which reported that the drought in southern Somalia was Africa's worst food catastrophe and it crossed the famine threshold since the famine of 1991/92. This result proved the study hypothesis which assumed that the drought in 2010-2011 was different among the drought years in the period of study.

Figure 16 a comparison between percent of change for different drought years in the study locations.
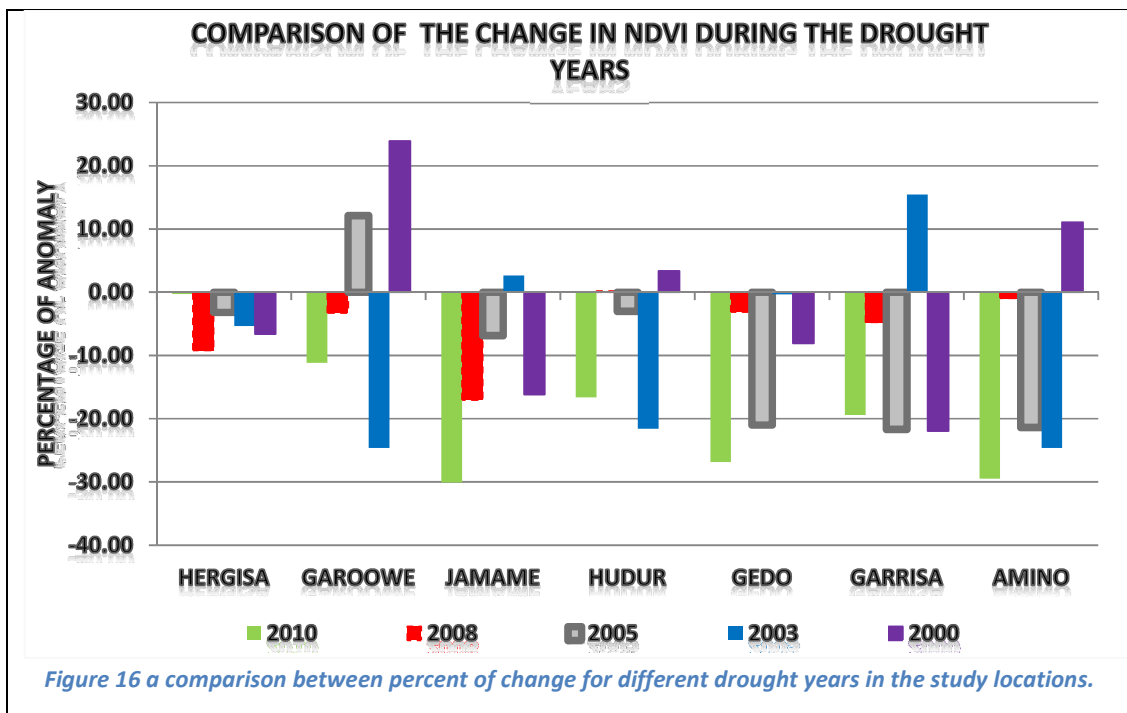
According to the results of the locations that were chose outside of Somalia (Garrissa and Amino), the intensity of 2010-2011 drought was the same and even worse as the results in figure 15. However, the impact of drought was in southwestern Somalia more than in northeastern Kenya and southern Ethiopia as it indicated by the FEWS NET reports. Three

possible reasons might explain this point: first is the conflict in southern Somalia that worsen the impacts of drought; second is the population density in southern Somalia (figure 7) which is higher than in northeastern and in northern Kenya. Three is the nature of livelihood in Somalia that is basically pastoralism. It depends entirely on rainfall which makes the country very vulnerable to drought.

Image of 2010 in figure 15 is not showing the intensity of the drought that was indicated by the other results in figure 13 and 14. The reason for that is the calculation method for the percent of change test at large-scale which calculated the difference between the annual maximum greenness and the mean of the annual maximum for every year. In the first season of 2010 there was above average greenness which influenced the annual mean. To avoid this problem, the annual mean should be taken for each year but due to the limitation in time, the test was not calculated using the annual mean. In 2011 the test was calculated for the first eight months which were dry months and then the impact of drought intensity was clear (figure 15- below image).

6.2. Drought onset and duration and its characteristics

In this part, results from NDVI were taken mainly into account due to the fact that relationship between rainfall and NDVI was not very strong which mean that rainfall is not the only factor influences vegetation phenology.

Four important points can be concluded from the results regarding the drought characteristic in southern Somalia and the region generally. First is that drought often starts in *Deyr* season (Oct.-Nov. short rainy season). Second important point is the drought duration which often continues in two sequential seasons like in the second season of 2001 and the first season of 2002, in the second season of 2003 and the first season of 2004, and in 2005-2006, 2008-2009 and 2010-2011. It is rare that drought happen in two seasons in the same year such as in 2000. Third important point is that duration of drought has a relationship with drought frequency as in the result in table 7. There is negative relationship with high slope which indicates that the frequency of short drought is higher than longer duration of drought. Similar results were mentioned that the country is frequently exposed to drought, occurring moderately every 3-4 years and severely every 7-9 years (Kundell, 2008). However, this kind of relationship needs longer time at local-scale analysis. The forth important point is that the dry spells often is followed by above normal greenness in the same pattern 2002-2003, 2004-2005, 2006-2007, 2009-2010 in most of the locations. In the second season in 2011, there is a above normal rainfall in most of the locations as in figure 14. These results were similar to the observations that are mentioned by NEWS NET's reports.

In northwestern Somalia, results indicated different pattern of rainfall, NDVI and drought years. In 2004 and 2009 there was a drought when in other parts especially in southern Somalia there was normal or above normal rainfall and NDVI (table 4 and appendices 2). The reason might be due to the rainfall pattern which tends be unimodal or inconclusive (two seasons are not clear separated) (Eklundh, 1996). Beltrando and Camberlin (1993) mentioned that there was a significant negative correlation between northern autumn rains in Somalia and the ENSO Southern Oscillation during the same season. This explains the above normal

greenness in this part during the drought years in 2005 and 2010 in the south and central parts of Somalia.

When compare NDVI and rainfall results with ENSO events (table 1), it is most likely that ENSO has a significant influence on the drought during the La Niña phase. ENSO can explain below normal rainfall in 2000, 2007-2008, 2010-2011 (moderate La Niña) and above normal rainfall in 2002-2003 (moderate El Niño), and in 2009-2010 (Strong El Niño). The other possible driver for the drought is the surface westerlies. Results of drought years in 2005 and 2008 were due the deficiency of autumn short rain according to Hastenrath et al (2007) and Hastenrath et al. (2010).

Results from z-test measured the difference between the mean of sample period and it showed that there was a significant difference between the means of the two periods 2000-2005 and 2006-2011 in half of the locations and not significant difference in the others. However, this test did not provide any indications about the drought onsets and duration during the study periods.

6.3. NDVI pattern

Results indicated that NDVI has the same pattern as rainfall with two seasons and two peaks in June and in November with time lag 1 month. This pattern is dominant in Somalia with slightly difference in Garissa (Kenya) where the first season onset and peak is a month earlier and a month later in second season. Similar results in east of Kenya regime mentioned by Martiny et al. (2006). In the northwest part, NDVI pattern is different with only one rainy season or two connect short seasons is dominant and it starts a month after rainfall starts in March and continues till September with decreasing in June. Results indicated the importance of second rainy season (Deyr). Although on Gu season in Somalia often more rainfall is received, the peak of NDVI in second season is higher which is agreed with the results mentioned by Martiny et al. (2006). The latter study suggested that rainfall in Deyr is more efficient than in Gu over most of the region. Also, it might be because of good distribution of Deyr rainfall as it was shown previously in figure 6. The importance of *Deyr* season on the variability of climate of East Africa was indicated by Hutchinson (1991), and Nicholson et al. (1996). It is mentioned that the main season (*Gu*) is less variable, so the interannual variability is often related primary to the second short season fluctuation.

6.4. Rainfall and NDVI correlation

Results indicated that the monthly correlations between monthly rainfall and mean monthly NDVI data were significant at 99% in most of the locations. However, rainfall is explained only third of NDVI in most of the locations as the coefficient of determination R^2 was from 25% to 35%. These results are lower than that have been done by some researchers e.g. Nicholson et al., 1990 and Martiny et al. 2006. The lack of strength relationship between the rainfall and NDVI might need more information from the ground which is not available in this study. The other factors which might influence vegetation at local scale are land use, overgrazing, soil type, fire and floods. In addition, late rainfall in the end of dry season might not sufficient to recover the failure of season.

Relationship between rainfall and NDVI indicated a better correlation with time lag one month for NDVI. It is the time needed for vegetation to response to the change in rainfall

which showed to be by one month in this study. Similar results in East Africa were mentioned by Eklundh (1998). Correlation between total monthly rainfall with mean, maximum and total monthly NDVI data showed that the mean monthly NDVI with monthly rainfall was given the best correlation. It might be because the mean value removes the positive bias in NDVI which is also a part of variation as well as negative effect (Eklundh 1998).

Seasonal correlation between the monthly mean of rainfall and NDVI in rainy months indicated that there is a difference between the first season and second season. Correlation in the second season is higher (significant in the majority of locations) than that in first season (significant only in Hergisa and even negative in some locations). This result support the hypothesis which assumed that the interannual variability is related primarily to the second short season fluctuation (section 6.3) and it also agreed with the result indicated by Nicholson et al. (1996) who mentioned that the fluctuation in second short season is primarily behind the interannual variability in rainfall. Negative correlation in first season can be explained by the fact that limited rainfall with high temperature in this time of year is not sufficient for vegetation to grow; evaporation exceeds the amount of rainfall received (Muchiri, 2007).

The annual correlation between annual mean rainfall and NDVI data was low and even negative in Jamame which could be explained by the results from spatial correlation which was performed for the annual cumulative of NDVI and rainfall. The results showed higher vegetation in comparison to the amount rainfall received because of the location of Jamame close to the Indian Ocean. Te wet current from the ocean bring a sufficient wet to the coastal area which allow vegetation to grow. Another reason might be the land cover in this part where it is mostly dry evergreen trees which resistant to drought.

6.5. Drought monitoring using remote sensing NDVI data

Remote sensing NDVI data provided by MODIS sensor was used to monitor drought in Somalia in the period of 2000-2011. The superiority of NDVI is that: it is easy to calculate and used; provided relatively freely to users and cover the entire globe. In country like Somalia where it is often difficult to obtain reliable or accurate meteorological data continuously due to the situation of the country, remote sensing data is the best data source available. In current study MODIS NDVI was able to detect the drought onset and duration in 2000, 2003, 2005, and 2008 and in 2010-2011 years which are also proved by FEW NET reports and scientific papers. NDVI data also was able to detect drought intensity especially the extreme intensity of 2010-2011 droughts. The most advantage thing for remote sensing is providing data at local, regional (figures 14 and 15) and global scale continuously every one to two days which is not available in any other data source. This makes it relatively easy to monitor any phenomenon in different time and spatial scale.

MODIS NDVI data has many advantages spatially and temporally in comparison to rainfall data which make it more practical. The spatial resolution of NDVI is 0.05 degrees (~5600 meter) and RE rainfall data is 0.1 degree which is higher than any kind of rainfall data available in this case (CRU rainfall data is only 0.5 degree). The spatial resolution of the data is very important in dry and semi-dry zones e.g. Somalia's climate where rainfall pattern is locative, erratic incidence, and unreliable (FAO, 1968; Muchiri, 2007). Also, NDVI has a temporal resolution of 8 days and RE rainfall data is a daily data whilst CRU rainfall data is

monthly data. Moreover, NDVI data available from 1981 until present (AVHRR data from 1981 and MODIS from 2000) which provide a reliable long-term vegetation data. Another thing is that rainfall data available from Climate Research Unit (CRU) is measured by rain gauges measurement stations and interpolation methods are applied for better estimation of rainfall. In Somalia, it is more likely that few meteorological stations are in operation and the quality of the data spatially and temporally are affected by the current situation in the country. It was reported that 1990-2004 period there was a gap and no significant data observed in that period due to the situation of the country (Muchiri, 2007). Then, the interpolation methods that were applied to estimate the rainfall data in Somalia might depend on stations that close to the country which might not represent the real data. Even though, particular attention has been set to the data quality and reliability but it is not recommended to use it to represent climate at a specific area or in sub-region (Mitchell et al. 2002).

There are some disadvantages related to the NDVI data itself and also to the using it to monitoring the drought. NDVI data has some limitations which are discussed in section 2.3.2. These limitations are the NDVI sensitivity to detect the saturation of vegetation; and from noise effect of background e.g. soil in low vegetation lands and from atmospheric aerosols. Another disadvantage that there is a time lag one month between the response of NDVI to the changes in rainfall which affect the detection of drought onset and termination. The last one is that there are some other factors that have the same impacts on vegetation as drought such as fire, overgrazing, temper and flood. However, it is unlikely that these factors have influence in most of study locations for long time.

6.6. Possible errors and uncertainties

There are some possible sources for errors or uncertainties can affect the results come from the data that was used in the study. Three of them are related to rainfall data, one to NDVI data and the last one is related to both of them.

The first one is the difference between the two sources of rainfall data that were used. CRU rainfall data was used for the period 2000-2009 and RE for the last two years (2010-2011). These two data might bring a systematic error, especially when we know that RF is remote sensing data and has disadvantage of overestimation in dry and semi-dry regions like Somalia. There should be some overlap years to compare them; but due to limitation in time for this study, it has not been done. However, the effect of this problem is limit when we know that RE data was able to detect drought onset, duration and intensity as in figure 11 and 14 which show that in 2010-2011 there was a larger decrease in rainfall in comparison with the previous years.

The second one is that the rainfall data has a strong positive skewness leading by the zeros in dry months. Positive skewness can affect the results by increasing the correlation between rainfall and NDVI, which we can notice as in table 3 where the seasonal correlation decreased. Also, rainfall data has outliers as we can see in appendix 1 affecting by some high records of precipitation in rainy months or errors in measurements. These outliers appeared in RE data, which has overestimation over dry and semi-dry zones. Outliers can affect the results by decreasing the correlation between rainfall and NDVI.

The third is that CRU rainfall data are gauges measurements and interpolation methods were used to give the best estimation of its spatial resolution (0.1 degree) (Mitchell et al. 2002). Increasing the number of stations and their good distribution will increase the accuracy of the data. However, there is still doubt about how many meteorological stations were used in the calculation in a country like Somalia with current unstable situation.

The forth possible factor is the difference between the spatial resolutions of the data. MODIS NDVI data has a spatial resolution of 0.05 degree (~5600 meter) while RE data has a 0.1 degree and CRU rainfall data has only 0.5 degree spatial resolution (10 times lower than NDVI data). Although, the study locations were chose as possible as it can in homogenous areas far away from water bodies, cities, valleys and rivers (20-30 kilometer), error and uncertainties might be possible in the results.

The last one is that NDVI data is 8-day product; but it acquires within 16 days as it explain in section 3.1. This procedure might bring some uncertainties to results, especially when detecting drought onset and termination as well as the correlation with rainfall data in a monthly step.

7. Conclusions

The most important results of the thesis can be concluded as follows:

- Although many dry years were reported, the drought in 2010-2011 was the worst as it continued for longer time than previous droughts during the study period (around 12 months). In most parts in southern Somalia, small parts of southern Ethiopia and most of northern and northeastern Kenya, there was extreme drought where the percent of negative change reached up to 30-50% below the normal.

- The impact of this drought was catastrophe because of existence of three factors which are the conflict in the country, nature of livelihood (pastoralism), and the population density.

- Drought often starts in Deyr season and continues to the Gu season in the next year e. g. 2003-2004, 2005-2006 and 2010-2011 and it is often followed by above normal rainfall. Also, droughts with long duration are lower frequent than that with short duration.

- The monthly correlation between rainfall and NDVI was significant at 99% significance in most parts of the country and surrounding areas, even though not very strong (r ~ 0.40). This relationship got higher with time lag one month for NDVI (r ~ 0.48). The correlation in the second rainy months (r = 0.43) was found to be higher than the first rainy months with almost no correlation (r = 0.08). Annual correlations were very low and even negative in Jamame.

- A remote sensing data proved to be a significant tool in monitoring and detecting drought components. In the thesis's case where rainfall data and other meteorological data were absence or unreliable, remote sensing data was the only practical choice. Another positive feature of remote sensing data is that it provides a large-scale overview of the drought situation.

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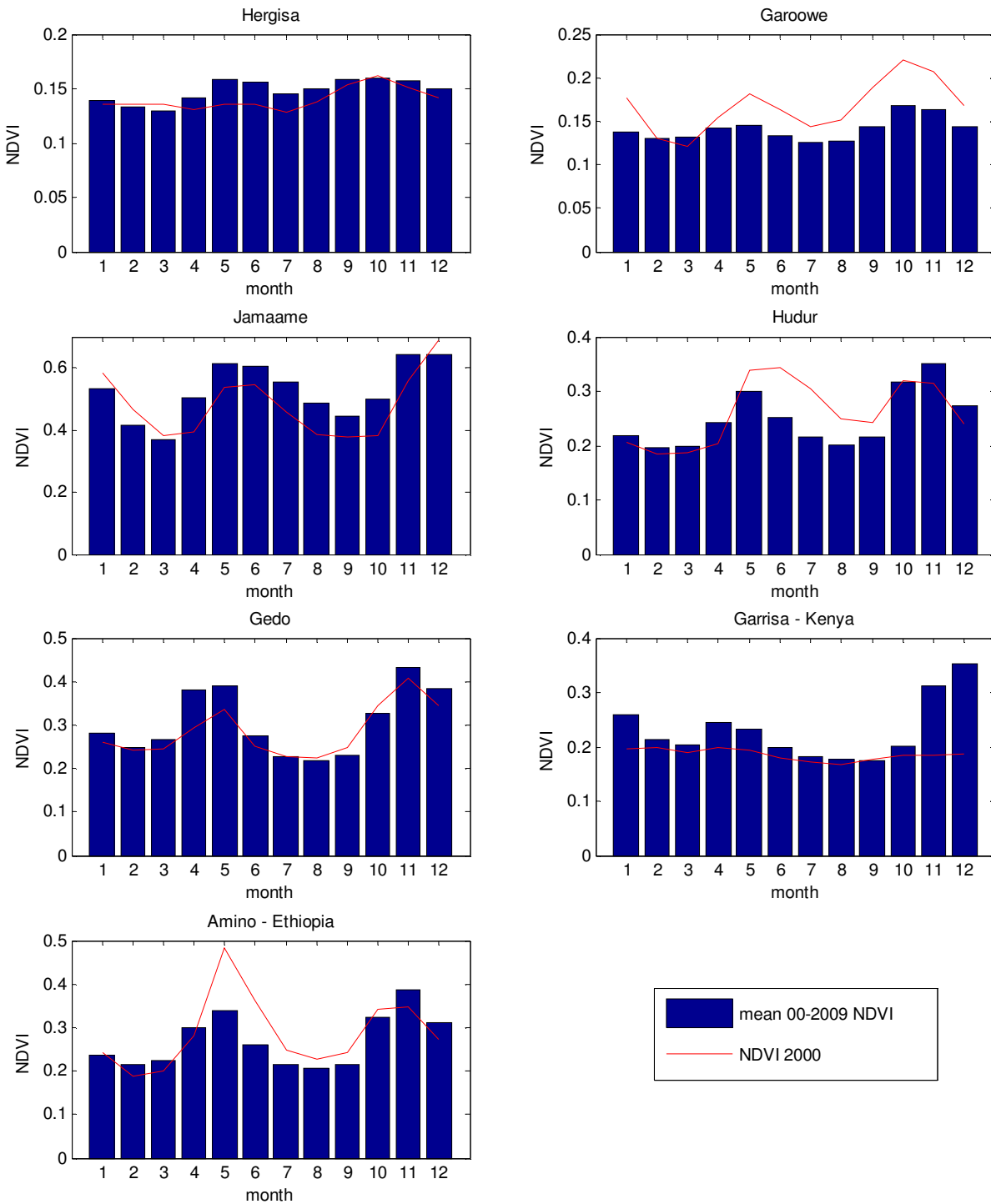http://www.case.ibimet.cnr.it/MTPprogramme/data/doc/4ClimateAnalysisTools/
DroughtIndices.pdf.

Appendices

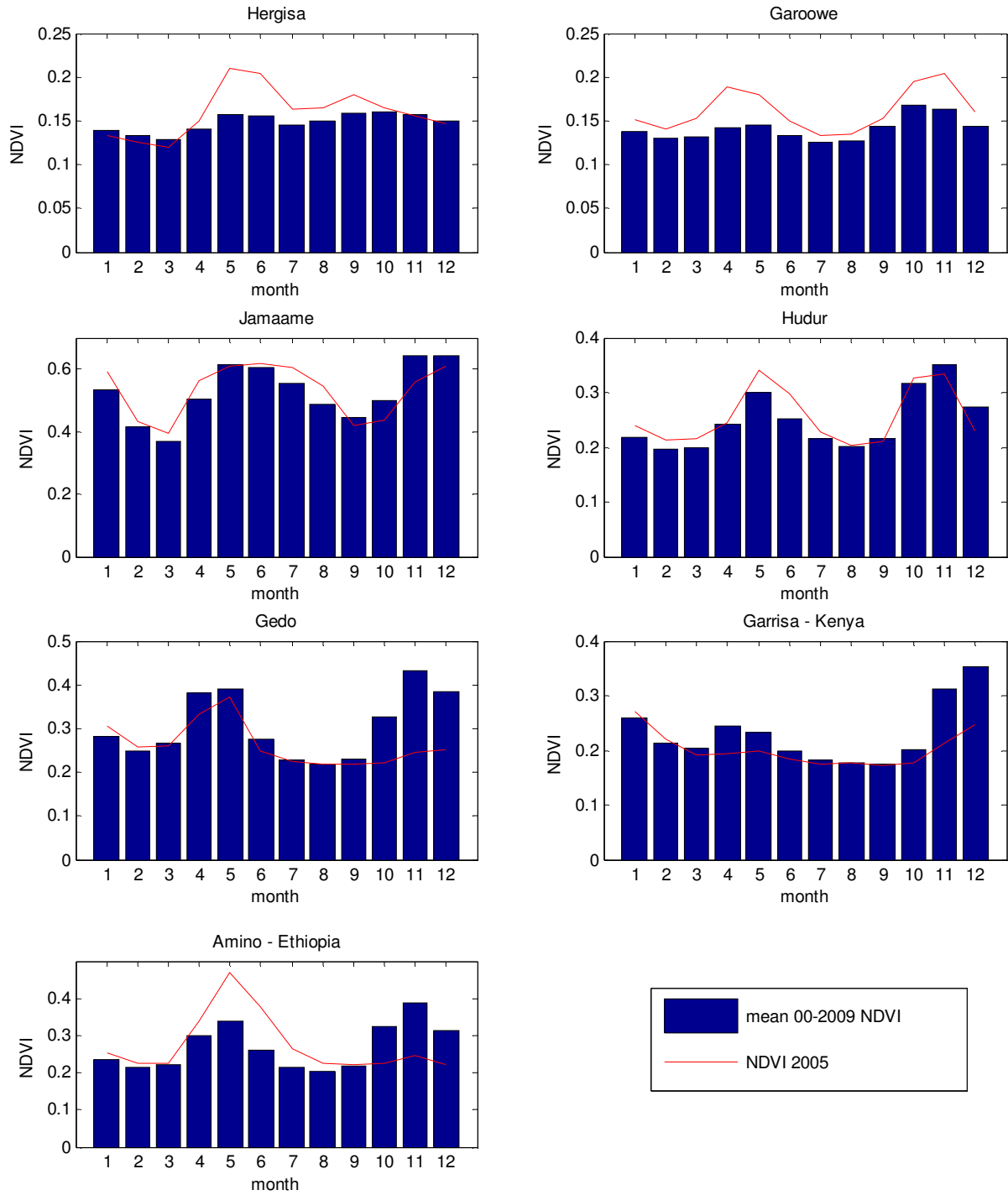**Appendix (1) linear regression of total monthly rainfall and different monthly NDVI data**

Monthly precipitation with monthly total NDVI - lag1

y = 0.0042x + 0.9955
R² = 0.3017

Monthly precipitation with monthly mean NDVI - lag1

y = 0.0012x + 0.2581
R² = 0.3465

Monthly precipitation with monthly max NDVI at lag - 1
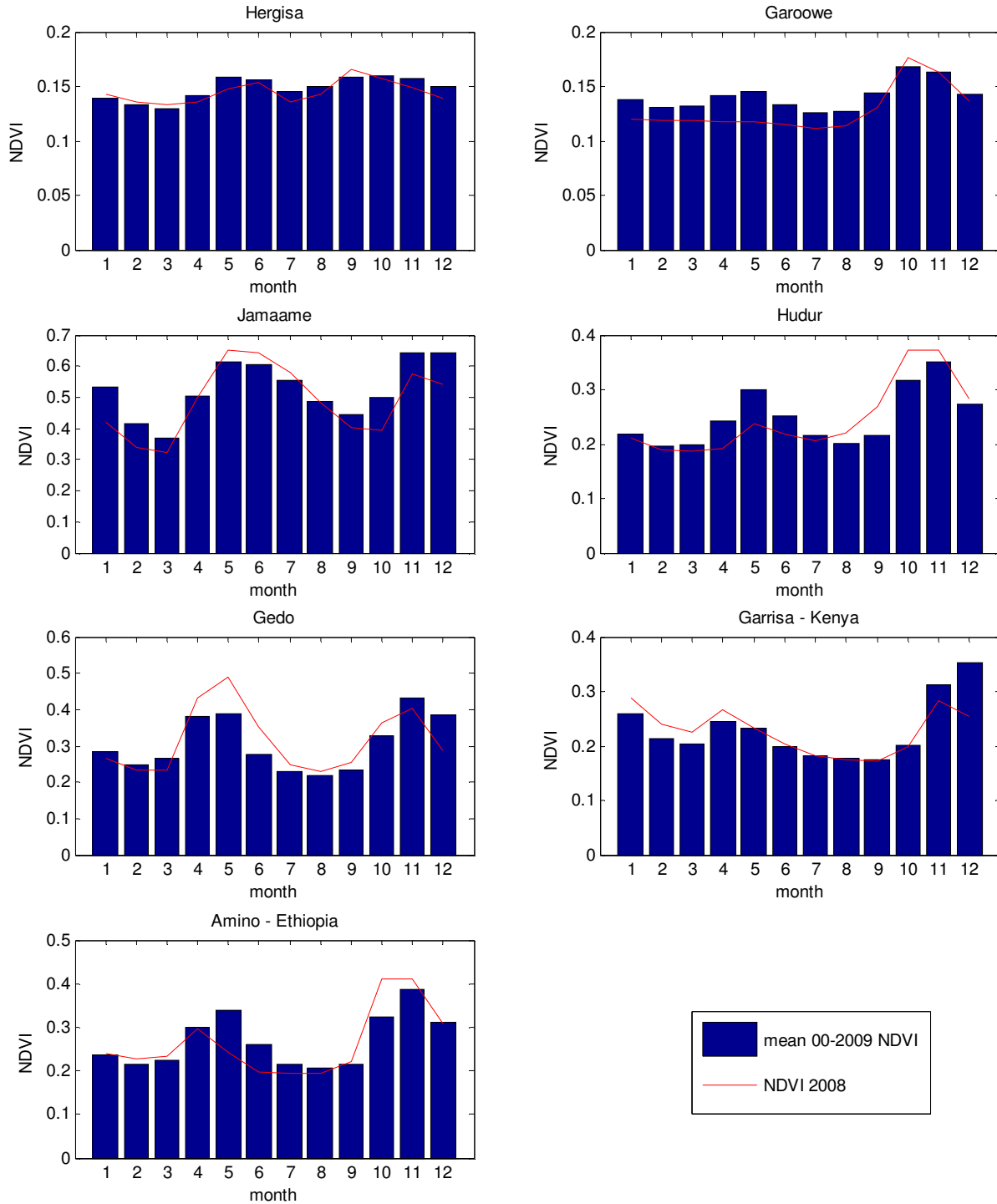
y = 0.0013x + 0.2781
R² = 0.3125
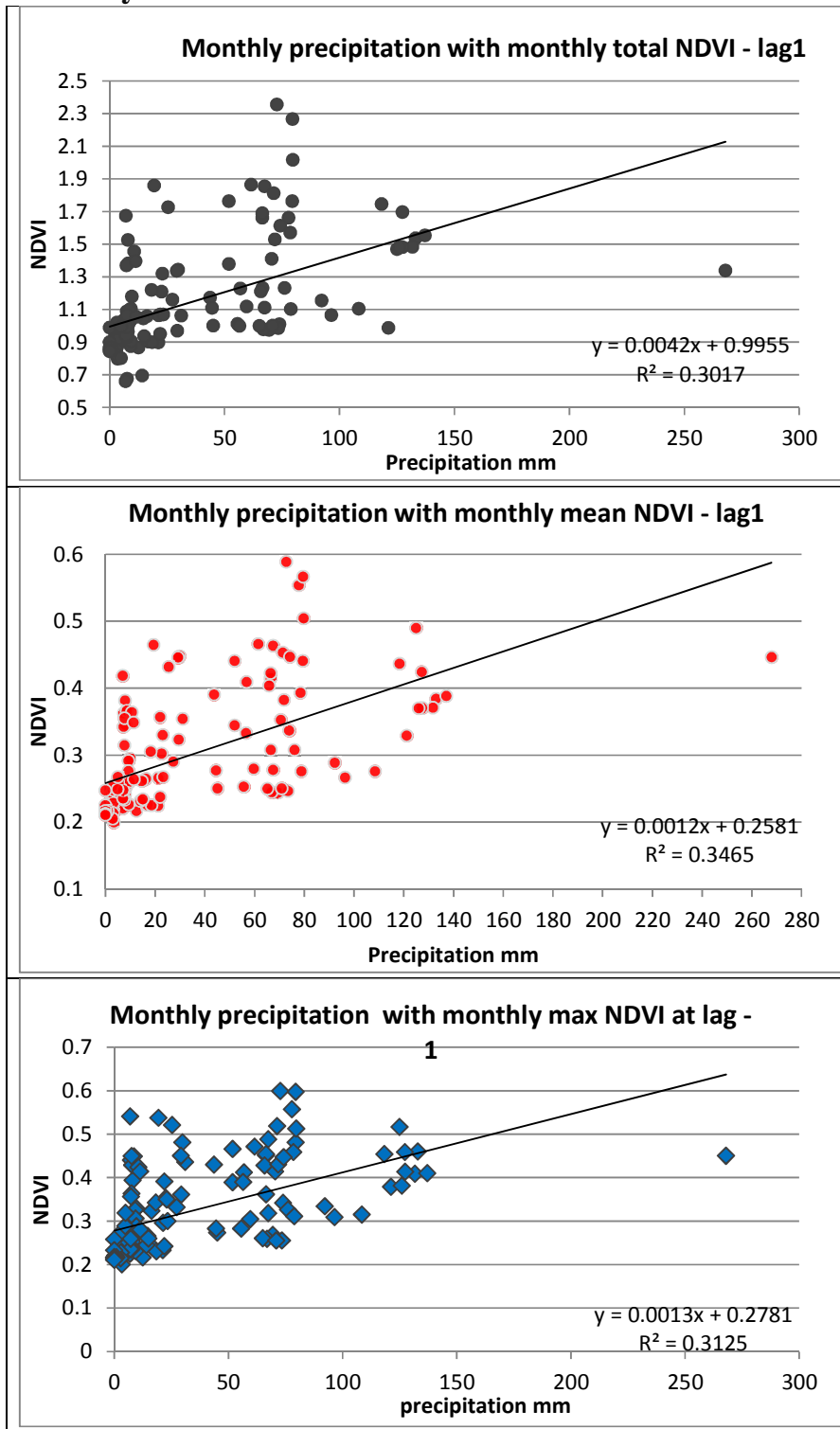
Appendix (2). NDVI variation in the period 2000-2011

NDVI pattern in 2000

NDVI in 2005

NDVI in 2008

NDVI variation in 2010
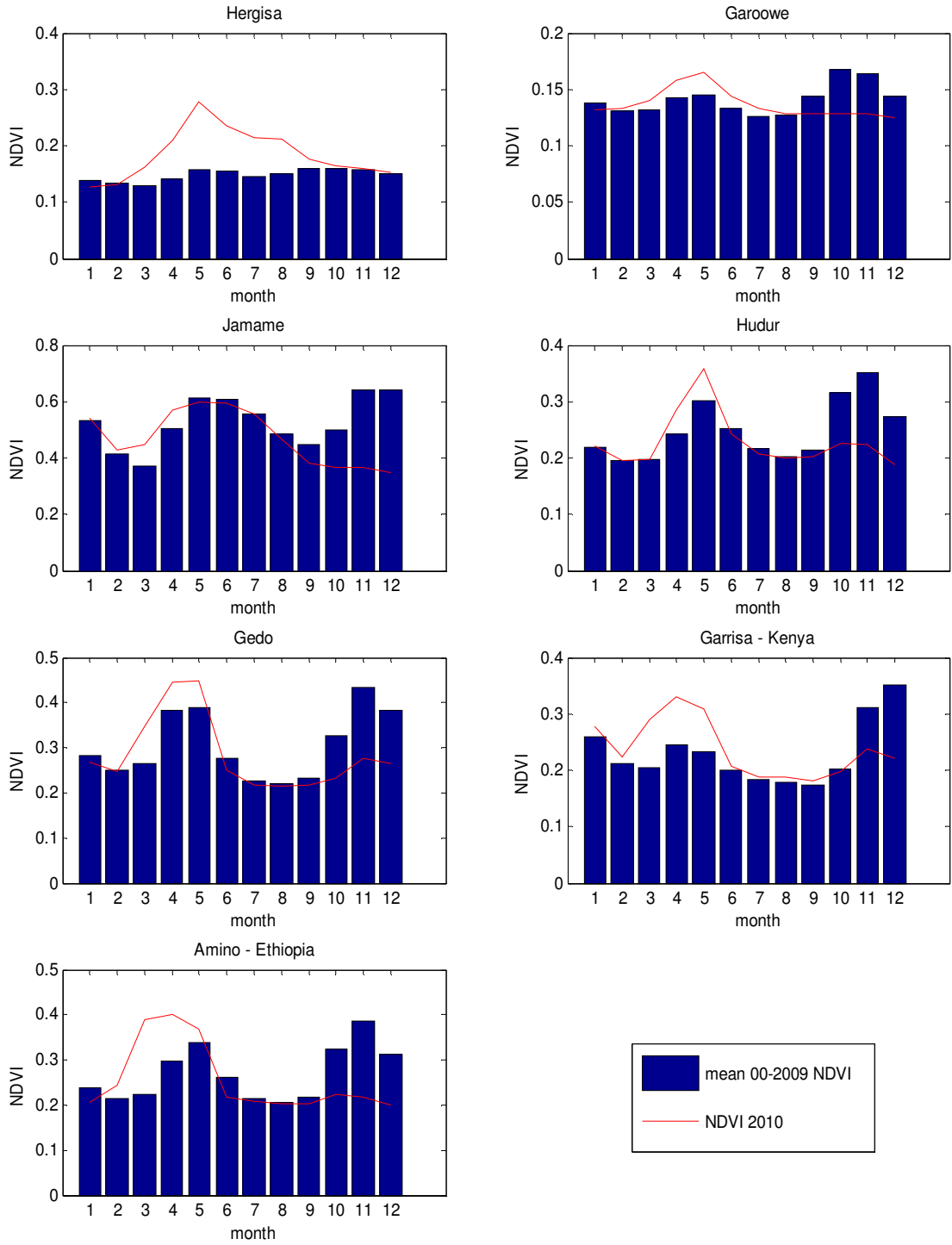
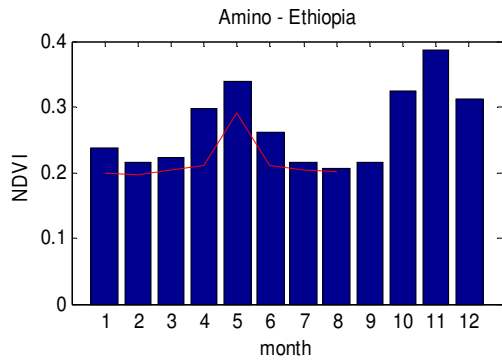# NDVI in 2011
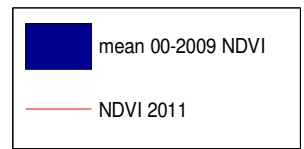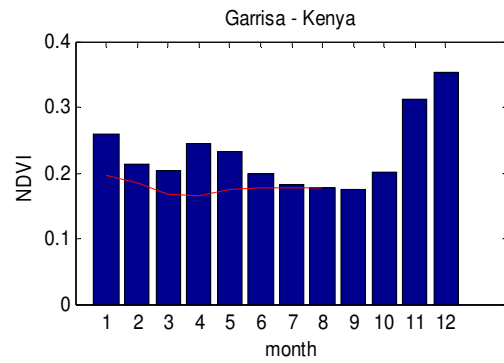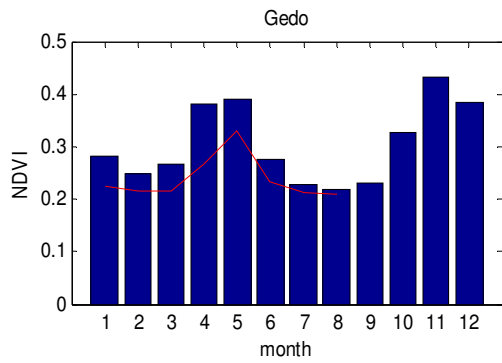
Appendix 3. Percentage of change

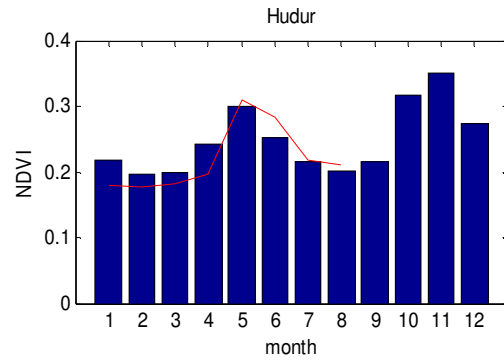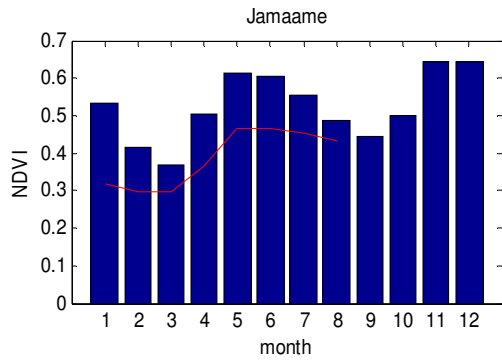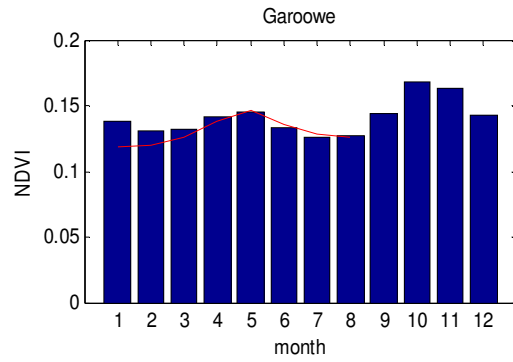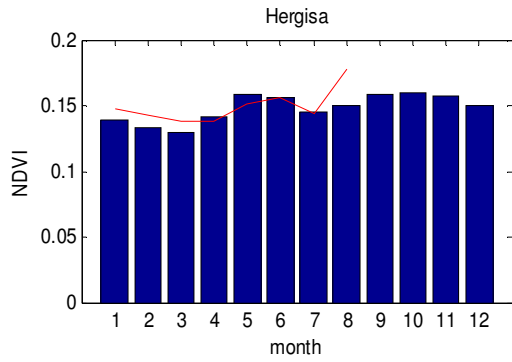| percent change of NDVI during the period 2000-2011 in the study places								
year	season	Hergisa	Garoowe	Jamame	Hudur	Gedo	Garrisa	Amino
2000	00-s1	-11.63	18.75	-14.50	11.55	-15.49	-15.47	25.42
	00-s2	-1.57	29.04	-17.82	-4.79	-0.65	-28.37	-3.31
2001	01-s1	5.84	-1.26	9.45	-6.46	2.72	-10.85	-17.53
	01-s2	-3.29	0.37	-8.51	-21.35	-29.82	16.49	-20.65
2002	02-s1	8.70	6.61	-5.42	-10.50	0.68	41.33	9.19
	02-s2	-1.39	-20.50	20.51	15.00	-6.97	3.85	15.08
2003	03-s1	-6.67	-5.03	7.80	21.63	8.41	12.31	14.26
	03-s2	-7.20	-29.33	-0.97	-41.20	2.35	23.59	-22.04
2004	04-s1	-3.53	-19.91	6.30	-1.98	-3.11	7.27	-27.13
	04-s2	-7.44	6.69	11.16	4.13	27.93	-2.13	14.76
2005	05-s1	23.68	23.38	3.90	11.25	-8.91	-14.74	31.79
	05-s2	0.78	20.44	-12.97	-0.90	-38.60	-23.99	-33.52
2006	06-s1	-7.15	3.74	-0.78	-5.05	-3.39	-19.34	-9.27
	06-s2	24.84	6.08	6.98	15.36	22.24	5.81	15.36
2007	07-s1	9.73	-0.33	8.10	9.59	4.67	-0.98	8.31
	07-s2	12.40	-20.73	7.54	10.29	14.48	2.56	21.97
2008	08-s1	-4.14	-16.69	4.06	-18.47	21.64	3.95	-17.70
	08-s2	-3.50	2.72	-15.12	11.85	1.00	-6.00	15.53
2009	09-s1	-14.82	-9.26	-18.90	-11.56	-7.23	-3.48	-17.34
	09-s2	-13.64	5.23	9.18	11.62	8.03	8.19	-3.18
2010	10-s1	58.52	11.09	2.57	11.42	9.09	25.16	9.89
	10-s2	1.81	-22.42	-35.56	-32.59	-33.03	-15.07	-38.06
2011	11-s1	-2.35	0.04	-24.64	-0.58	-20.61	-23.78	-20.87

Percent change of rainfall during the period 2000-2011 in the study places								
year	season	Hergisa	Garoowe	Jamame	Hudur	Gedo	Garrisa	Amino
2000	00-s1	-32.47	-0.53	-40.05	-23.93	-33.69	-55.36	-48.40
	00-s2	56.50	12.25	13.14	-6.67	-24.42	-17.02	-15.91
2001	01-s1	-9.24	-0.53	10.43	3.89	4.09	-13.13	8.93
	01-s2	58.91	1.14	75.47	-0.05	7.70	58.18	0.04
2002	02-s1	-29.72	-6.85	-30.93	12.38	20.96	-5.11	53.66
	02-s2	28.70	13.11	-45.01	2.28	-7.67	-66.73	8.24
2003	03-s1	-13.98	-0.53	-27.17	-2.25	-4.82	-22.52	-17.87
	03-s2	-26.28	-7.98	-4.22	-0.50	2.06	11.78	-5.29
2004	04-s1	101.53	9.09	-27.53	0.45	-3.30	-26.46	-6.74
	04-s2	35.35	0.85	43.04	-2.53	3.66	27.34	-12.41
2005	05-s1	-10.16	-0.53	53.08	3.32	1.46	27.94	6.03
	05-s2	-26.28	-7.98	-13.85	0.17	0.33	-18.07	-0.27
2006	06-s1	-0.08	1.19	53.54	5.04	19.39	69.31	17.62
	06-s2	-49.24	-6.27	9.59	-0.43	5.82	5.80	-1.54
2007	07-s1	-18.87	-0.26	5.43	-1.90	-4.06	12.82	-17.59
	07-s2	59.52	17.09	-26.64	6.41	9.99	-10.52	31.57
2008	08-s1	2.37	-0.53	-23.00	3.89	0.50	-12.46	9.94
	08-s2	-68.58	-11.11	-22.46	0.17	9.85	14.05	-4.47
2009	09-s1	10.62	-0.53	26.19	-0.87	-0.52	24.97	-5.59
	09-s2	-68.58	-11.11	-29.05	1.15	-7.32	-4.83	0.04
2010	10-s1	214.51	-14.30	110.97	-24.08	-59.71	-52.94	-63.04
	10-s2	157.01	-48.78	-55.43	-73.00	-61.06	-68.75	-97.89
2011	11-s1	214.51	-45.98	-77.85	-57.55	-80.75	-90.81	-87.79
	11-s2	157.01	-37.32	224.34	87.12	240.68	27.75	100.22

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