Analysis of Past and Future Intra-Seasonal Rainfall Variability and its Implications for Crop Production in the North Eastern Amhara Region, Ethiopia

MSc. Thesis

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Analysis of Past and Future Intra-seasonal Rainfall Variability and its Implications for Crop Production in the North Eastern Amhara Region, Ethiopia

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Master of Science in Agro-Meteorology and Natural Risk Management

Muluneh Getaneh Tegegn

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POST GRADUATE PROGRAM DIRECTORATE

We hereby certify that we have read and evaluated this thesis entitled **Analysis of Past and Future Intra-Seasonal Rainfall Variability and its Implications for Crop Production in the North Eastern Amhara, Ethiopia** prepared under our guidance by Muluneh Getaneh Tegegn. We recommend that it be submitted as fulfilling the thesis requirement.

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As member of the Board of Examiners of the Final MSc Thesis Open Defense Examination**,** we certify that we have read and evaluated the Thesis prepared by Muluneh Getaneh Tegegn and examined the candidate. We recommend that the thesis be accepted as fulfilling the Thesis requirements for the Degree of Master in Agro-meteorology and Natural Risk Management.

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DEDICATION

I dedicate this thesis to the Almighty God for he has given me many friends, who were with me in the journey of life to be what I am today.

STATEMENT OF THE AUTHOR

First, I declare that this thesis is my own work and that all sources of materials used for this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements for an advanced MSc degree at Haramaya University, Ethiopia and is deposited at the University Library to be made available to borrowers under rules of the library. I solemnly declare that this thesis has not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

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BIOGRAPHICAL SKETCH

The author, Muluneh Getaneh, was born in September 05/ 1976 in Lasta, North Wello Zone of the Amhara Regional State of Ethiopia from his father Getaneh Tegegn and his mother Fantaye Semagn Adugna. He attended his primary and secondary education at Assosa Elementary and Secondary School at Asossa, Benshangul Gumuz Region, respectively. He joined Arba Minch University in 2004 and graduated with Advanced Diploma in Meteorology Sciences in July 2006. Soon after his graduation, he was employed by National Meteorology Agency of Ethiopia as Meteorological Officer and served with this capacity until 2010, and then promoted to the position of Higher Meteorological Technician at Bahir Dar branch. While in service, he attended a degree program at Bahir Dar University and graduated with BSc degree in Disaster Risk Management and Sustainable Development in June 2012. He joined the Post Graduate Program at Haramaya University in October 2013 to pursue his MSc degree in Agro-Meteorology and Natural Risk Management.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANRS	Amhara National Regional State
AR4	Forth Assessment Report
AR5	Fifth Assessment Report
CMIP5	Coupled Model Inter comparison Project Phase 5
CSA	Central Statistics Agency
CSIRO	Commonwealth Scientific and Industrial Research Organization
CV	Coefficient of Variation
DOY	Day of Year
DSA	Development Studies Associates
ECA	Economic Commission for Africa
EIAR	Ethiopian Institute of Agricultural Research
ENSO	El Niño Southern Oscillation
EOS	End of Season
ETo	Reference Evapotranspiration
FAO	Food and Agriculture Organization
GCMs	Global Circulation Models
GDP	Gross Domestic Product
GHES	Green House gas Emission Scenario
HS	Hargreaves and Samani
INSTAT	Interactive Statistical Processing Package

IPCC	Inter-Governmental Panel on Climate Change
IPFRI	International Food Policy Research Institute
ITCZ	Inter Tropical Convergence Zone
LGS	Length of Growing Season
MIROC	Model for Inter disciplinary Research on Climate
MoA	Ministry of Agriculture
MoARD	Ministry of Agriculture and Rural Development
MoFED	Ministry of Finance and Economic Development
NAPA	National Adaptation Program Action
NMA	National Meteorology Agency
NMSA	National Meteorology Service Agency
RCP	Representative Concentration Pathways
RMSE	Root Mean Square Error
RSCZ	Red Sea Convergence Zone
SCI	Shawel Consultant International
SD	Standard Deviation
SE	Standard Error
SOS	Start date of Season
SRA	Standardized Rainfall Anomaly
SSA	Sub-Sahara Africa
STJ	Sup Tropical Jet
TEJ	Tropical Easterly Jet
UNDP	United Nations Development Program

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Analysis of Past and Future Intra-seasonal Rainfall Variability and its Implications for Crop Production in the North Eastern Amhara Region, Ethiopia

ABSTRACT

Rainfall is the most important but variable climatic element in semiarid regions. The present study analyzed intra-seasonal rainfall variability, its trends and implications of rainfall change and variability risk on crop production at four stations located in the semiarid North Eastern Amhara Region as in put variables observed (1992-2012) and future projected (2021-2040) daily rainfall data were used. The observed daily rainfall data were obtained from the National Meteorology Agency (NMA) while future daily rainfall data were downscaled for three Global Circulation Models, GCMs (CSIRO-Mk3-6-0, Had GEM2-ES and MIROC-ESM-CHEM) under the 4.5 representative concentration Pathway (RCP) using MarkSim weather generator. After quality control, the rainfall data were subjected to computation of rainfall variability indicator indices such as rainfall totals, rainfall start and end dates, length of growing period (LGP), number of rainy and dry days, and length of dry spells using INSTAT 3.36 software. The analyses of observed data revealed that annual, seasonal Kiremt and Belg rainfall totals were characterized by low amount, short duration, early cessation and high dry spell probabilities for both Kiremt and Belg seasons. The analysis also indicates that the Belg season has been failing increasingly (33-66%) in the region and it is projected to worsen in the future. The projected increasing change in rainfall totals and decreasing change in rainy days indicated that the future Kiremt season will probably experience water logging/flood over the majority stations and this will affect crop production. The GCMs used in the study agreed on reduction of rainfall amount in the Belg season and shortening of the LGS in both the Belg and Kiremt seasons by 2030s at all the studied stations. The implication of the results is that crop production during the Belg season will be risky even for drought tolerant crops as the projected mean LGP in the region will be in the range of 28-54 days only. According to models projection, a combination of early onset of Kiremt and late start of Belg seasons could be advantageous for relatively long maturing and dry spell tolerant crops such as sorghum and millet. Supplemental irrigation from rainwater from month of July and August in which maximum rainfall will be found may be possible for the dry month of September.

Keywords: rainfall variability, crop production; North Eastern Amhara, Dry spell, LGS

1. INTRODUCTION

Climate variability and change are affecting the whole world (IPCC, 2007). The impacts are significantly negative on rain fed agriculture (Travis *et al*., 2010) on which the economies of most developing countries depend (Lamboll *et al*., 2011) with less adaptive capacity (Michael, 2006; Yesuf *et al.,* 2008; UN-OHRLLS, 2009). Particularly, many low income countries, located in the tropical and sub-tropical region are vulnerable to shifting and variable climate (Joachim, 2008). Africa in general and Sub Saharan Africa (SSA) in particular is the most vulnerable region in the world to climate variability and climate change (Michael, 2006). In SSA, temperature has increased by 0.7 °C over the last century and projected to increase by 3.2-3.4 °C by 2050-2090 (Attri and Rathore, 2003; FAO, 2011; Beddington *et al*., 2012). In recent decades, the raising temperature is associated with increased spatial and temporal variability in amount and distribution of rainfall that exceeded the long term spatial and seasonal variability (Ayalew *et al.,* 2012; Taye *et al*., 2013).

Ethiopia, being part of SSA, has been experiencing a series of climatic vagaries with many episodes of cyclic droughts and flood that claimed the lives of thousands of people and slashed economic development. Over the last 50 years alone, the country was hit hard by drought in 1952, 1959, 1965, 1972, 1973, 1978, 1984, 1991, 1994, 1999 and 2002 whereas it experienced wet conditions and occasional floods in 1958, 1961, 1964, 1967, 1968, 1977, 1993, 1996, 1998 and 2006 (Haile, 1988; Gissila, *et al*., 2004; NMA, 2007).

Despite such adverse events, the average total annual rainfall over the country remained fairly stable over the last 50 years (NMA, 2007). However, a closure look of the trend at regional and local levels indicates strong variability. For example, over the eastern, southern, and south western parts of the country, Seleshi and Zanke (2004) found increasing trends in the annual rainfall, but no change over the central, northern and north western parts of the country (Seleshi and Zanke, 2004). Nevertheless, disaggregated studies revealed different (positive, negative or no) trends among station in the north western, northern and central parts of the country (Ayalew *et al*., 2012; Hadgu *et al*., 2013; Kassie *et al.,* 2014). Future predictions have also shown more variable conditions (McSweeney, 2008) making adaptation planning difficult for larger areas

The North Eastern Amhara Region which consists of North Wello and South Wello semi-arid Zones is probably the region most experienced climate change and variability in history of the Ethiopia. According to Degefu (1987), this region is suffered most from one of the worst drought that induced famine. The drought of 1973-1975 killed at least 40 thousand people in Wello (ECA, 1984; Degefu, 1987). Again in the same region and the adjoining areas, drought of 1983-1985 claimed an estimated 400 - 800 thousand human lives ever recorded in the century long history of the country. Subsequently dozens of farmers have been forced to relocate and settle in other parts of the country where conditions are believed to be satisfactory for reliable crop production (Degefu (1987).

This adverse historical situation in the North Eastern Amhara Region could partly be because of increased rainfall variability which is associated with global warming. According to Bewket (2009), crop production is significantly associated with rainfall distribution in its onset, cessation and amount during rainy season. Hence changes in timing of onset disrupt farmers' practices of land preparation and sowing while its distribution and cessation greatly affects crop growth, yield formation and harvesting. According to Hadgu *et al.* (2013), analysis of trends in rainfall events such as onset, cessation, dry spell, wet spell and number of rainy days is more important than annual and seasonal totals in the drylands where seasonal rainfall variability is high.

Previous studies in many parts of Ethiopia emphasized on analysis of trends in annual and seasonal rainfall totals (Mekasha *et al.*, 2014) disregarding intra-seasonal rainfall variability such as timing of season start date and season end date , number of rainy and dry days, dry spells at different lengths and other vital aspects of rainfall variability for agricultural planning. So far, only few studies (Ayalew *et al.,* 2012; Hadgu *et al*., 2013; Kassie *et al*., 2014) have attempted to partly address these issues with limited number of stations in the north western, northern and central parts of the country although studies of the past seasonal rainfall patterns and future expectations of the event at local levels is essential for planning and designing appropriate climate change adaptation strategies (Thornton *et al.,* 2009; Kassie *et al.,* 2014). Understanding the nature of past and future climate variability is important for increasing crop productivity and buffering situations where increased stresses are likely to occur (Lane and Jarvis, 2007; copper *et al*., 2009; Thornton *et al.*, 2009; Sarr, 2012; Kassie *et al*., 2014) as in the case of North Eastern Amhara National Regional State (ANRS).

Scope of the study

The present study analyzed the past and future intra seasonal rainfall variability at four locations in the North Eastern Amhara. Moreover, the study examined the trend and discuss the implication of rainfall variability risk for crop production during 1992-2012 and by 2021-2040 in the North Eastern Amhara. The study was carried out using observed and downscaled climate data sourced from the Ethiopian Meteorological Service Agency and downscaled from MarkSim GCMs and soil data from literatures.

Research questions

- Was there intra seasonal rainfall variability in the North Eastern Amhara during 1992-2012?
- How was the trend in intra seasonal rainfall indices for the last 21 years in the North Eastern Amhara
- What will be the pattern of future rainfall in North Eastern Amhara Region by 2030?
- Was there crop failure during the last 1992-2012 due to onset failure in the North Eastern Amhara?
- Could *Belg* growing season exist, shift or diminish by 2030 in the North Eastern Amhara?
- Relative to the base period, what are the expected changes in intra seasonal rainfall indices including length of growing season in the North Eastern Amhara?

Problem of the study

- Previous studies in many parts of Ethiopia emphasized on analysis of trends in annual and seasonal rainfall totals (Mekasha *et al.*, 2014) disregarding intra-seasonal rainfall variability and its effect on rain fed crop production.
- Although the North Eastern Amhara semi-arid region is characterized by high rainfall variability, crop failure and recurrent drought occurrence, the area is not studied
- No one knows how look like the future climate condition for North Eastern Amhara

Therefore, the major aim of this study was to analyze past and future intra-seasonal rainfall variability and discuss its implication for crop production in the North Eastern Amhara Regional State of Ethiopia.

Specific objectives

- To analyze variability of past and future intra seasonal rainfall indices in the study area,
- To examine the trend of past and future intra seasonal rainfall indices, and discuss the implications of variability and change risk for crop production in the study area.

Significance of the study

The findings of this study can be used as inputs for decision makers enable to select suitable crops/varieties, enable policy makers to get prepared to the negative impacts on crop production and as reference/baseline for further studies.

2. REVIEW OF LITERATURE

2.1. Definition and Concepts of key words

The following sub-section briefly explains key concepts used in this thesis. More detailed explanations can be found in IPCC (2001) and Nakicenovic *et al*. (2000).

Weather: it is the fluctuating state of the atmosphere around us. Weather is what you feel, for instance, you may feel hot or cold when you arrive Addis from Humera that is weather.

Climate: Climate is typically defined in terms of 30 year means, and higher-order moments about those means which implicitly assumes stationarity of a given climate state. Climate is what you expect, for instance, if you expect that the future Kiremt will be dry that is climate.

Climate variability: variation in the mean state and other statistics (such as standard deviations, occurrence of extremes, etc.) of climate on temporal and spatial scales beyond that of individual weather events. Variability may be due to natural processes within the climate system (internal variability), or due to anthropogenic forcing (external variability).

Climate change: A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcing or to persistent anthropogenic changes in the composition of the atmosphere or in land use systems.

Representative Concentration Pathways (RCPs): Plausible representation of the future development of emissions of greenhouse gas concentrations based on coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change) and their likely relationships.

Model Calibration: it refers to adjustment of parameters of a model so that simulated results reach a predetermined level, usually that of an observation whereas model evaluation involves comparison of outputs of a calibrated model with an independent data set and determination of suitability for an intended purpose.

Uncertainty: An expression of the degree to which a value (e.g., the future state of the climate system or its impact) is unknown.

2.2. Agro-Climatic Zones and Seasons in Ethiopia

Three major climatic zones which have been known since ancient times in Ethiopia due to varied topography are *Dega*, *Weina Dega* and the *Kolla*. The *Dega* (also known as the cool zone) occurs in the central sections of the western and eastern parts of the north- western plateau. The elevation of this region is above 2400m, and daily temperature ranges from near freezing to 16^0c while the *Weina Dega* (the temperate zone) ranges from between 1500m and 2400m in elevation, and consists of parts of the central plateau. The kola or hot zone generally comprises areas lower than 1500m in elevation, the Denakil depression and the Blue Nile valley (NMSA, 1996; Cheung *et al.*, 2008).

According to NMSA (1996), three distinct seasons locally known as *Bega* (October to January), *Belg* (February to May) and *Kiremt* (June to September) are observed in Ethiopia. Of these three seasons, *Kiremt* is the main rainy season, in which about 85% to 95% of the food crops of the country are produced (Degefu, 1987; NMSA, 1996; Mesay, 2006).While Rainfall distribution and amount during *Belg* season is highly variable in time and space (NMSA, 1996; Mesay, 2006).The western half of the country, with one dry and one wet season in a year, receives the highest amount of rainfall in *Kiremt*, which is generally decreasing from 10 months in the south west to only 2 months in the north west (NMSA, 1996; Mesay, 2006; Viste *et al.*,2012). The central and south-eastern high lands and the adjoining lowlands experience all the three seasons and receives about 60% of the total annual rainfall during the *Kiremt* (NMSA, 1996). The southern and south-eastern low lands of the country have a bi-modal rainfall pattern with main rainy season occurring from March-May and the second short rains from September-October. On the other hand, the north eastern part of the country receives very small amount of *Kiremt* rainfall in a year (Mesay, 2006; NMSA, 1996; Viste *et al*., 2012).

According to Funk *et al*. (2005); Mesay (2006) and McSweeney *et al.* (2008), seasonal rainfall in Ethiopia is driven mainly by the migration of the tropical rain belt, the Inter-Tropical Convergence Zone (ITCZ). Moreover, the main season (*Kiremt*) rain-producing systems such as the ITCZ, cross equatorial flow from (Mascarene high) southern Indian Ocean, moisture flow from (St. Helena high) Atlantic Ocean and the monsoon low and the associated trough have a great role to play for main season (*Kiremt*) rainfall performance over Ethiopia. According to Mason and Goddard (2001), El Niño–Southern Oscillation (ENSO) have an impact on a seasonal shifting of the normal rainy seasons in some regions, as a result a shortening or lengthening of the rainy seasons, particularly over tropical regions. In line with this, Gissila *et al*. (2004) and Segele and Lamb (2005) indicated that there could be a significant teleconnection linkage between ENSO and the Ethiopian *Kiremt* rainy season. The correlation showing that rainfall could be below average through El Niño episode further more high drought probabilities during strong El Niño years whereas, La Niña events favored further temporal expansion of seasonal activities beyond the normal duration of the rainy season over a region (Gissila *et al*.,2004).

However, Conway (2009) and Conway and Schipper (2011) noticed d that despite clear evidence on the consequences of climate change, the drivers of climate change in the country are poorly understood. In Ethiopia, the distribution of rainfall varies over the diverse agro-ecological zones that exist in the country (Viste *et al*., 2012) and the appearance remains usually not understood (Conway and Schipper, 2011).

2.3. Weather Systems Producing Seasonal Rainfall over Ethiopia

Ethiopia lies in the horn of Africa approximately at 3^0-15^0N latitude and 33^0-48^0 E longitude which has an implication on atmospheric circulation. The country's topography is composed of massive highland complex of mountains and dissected plateaus divided by Great Rift Valley running generally south west to north east (Mersha, 1999). The seasonal and annual rainfall variations are the result of the micro-scale pressure systems and monsoon flows which are related to the changes in the pressure systems (Haile, 1986; Beltrando and Camberlin, 1993; NMSA, 1996 and Conway, 2009). The movement of the ITCZ is sensitive to variations in Indian Ocean sea surface temperatures and vary from year to year, hence the start date, end date and duration of the rainfall seasons vary considerably inter-annually.

The most well documented cause of this variability is the El Niño Southern Oscillation (ENSO). Warm phases of ENSO (El Niño) which is associated with reduced rainfall in the main rainfall season (*Kiremt*)in north and central Ethiopia, causing severe drought and famine, but also with enhanced rainfalls in the earlier February to April rainfall season which mainly affects the rainfall distribution in the southern Ethiopia (McSweeney *et al.*,2008). The most important weather systems that cause rain over Ethiopia includes Sub-Tropical Jet (STJ), Inter Tropical Convergence Zone (ITCZ), Red sea Convergence Zone (RSCZ), Tropical Easterly Jet (TEJ), and Somalia Jet (NMSA, 1996b).The major dominant weather system is ITCZ. It oscillates seasonally with in the tropics and its surface position is influenced by topography and local eddies. Thus, this seasonal oscillation of the ITCZ causes a variation in the pattern of wind flows over Ethiopia (Romilly and Gebremichael, 2010).

According to Mesay (2006), the major synoptic features that influence the weather of Ethiopia include Easterly wave (EW), Sub-tropical Jet Stream (STJ) extra-tropical troughs, Red Sea Convergence Zones (RSCZ), anticyclone over the Indian Ocean and the Mediterranean depression. Moreover, the intensity and areal coverage of the rain is associated, to a great extent with the intrusion and passage of the north -south oriented mid- latitude trough in the westerly wind field. The TEJ and the Tibetan anticyclone are the two important upper level atmospheric features. The strength and position of these atmospheric systems vary from year to year and the rainfall activity too. Regional and global weather systems affecting *Kiremt* (JJAS) season in Ethiopia include the ITCZ with the dominant effect and the Maskarana High pressure in Southern Indian Ocean, the Helena High pressure Zone in the Atlantic, the Congo air Boundary, the Monsoon depression and trough, the Monsoon clusters and the Tropical Easterly Jet (Kassahun,1999). Philander (1990) mentioned that El Niño events are associated with variability in rainfall in equatorial East Africa, like Ethiopia (IPCC, 2007).

It has been also noted that the rainfall is highly variable in amount, distribution and becomes unpredictable across regions and seasons (Mersha, 1999; Tilahune, 1999; Tesfaye and walker, 2004; Ayalew *et al*., 2012). This variability of rainfall and the recurrent droughts in Ethiopia affects the lives of millions of people as livelihood depends on rainfall (Viste *et al*., 2012). Among the regions that are vulnerable to recurrent drought in Ethiopia, the North Eastern Amhara Region is the most affected one (NMA, 2007; Viste *et al*., 2012).

2.4. Trend of Seasonal and Annual Rainfall Variability in Ethiopia

Over the last decades various studies have been conducted to examine rainfall trends in Ethiopia (NMSA, 2001; Osman and Sauer born, 2002; Bewket and Conway, 2007; Seleshi and Camberlin, 2008; Viste *et al*., 2012; Hadgu *et al.*, 2013). NMSA (2001) reported significant reduction in annual rainfall in the north and southwest part and conversely an increasing trend in the central part of the country. However Bewket and Conway (2007) observed inconsistent trends in the annual, *Kiremt* and *Belg* rainfall among different stations in the country.

According to Bewket and Conway (2007) for the period of 1975 to 2003, *Kiremt* and annual rainfall showed significant increasing trend at Dessie and Labella and conversely significant decreasing trend at Debre Tabor. Meze-Hausken (2004); Seleshi and Camberlin (2006) and Cheung *et al*. (2008) did not find any significant trend over the northern and north eastern part of the country. Hadgu *et al*. (2013) also showed a declining trend in annual and seasonal rainfall amounts in northern Ethiopia, but the trends were non-significant at most of the stations he studied. As indicate by Hadgu *et al*. (2013), start date of growing season showed increasing trend whereas, end date and length of growing season declining trend in the northern Ethiopia

2.5. Rainfall Variability and Agriculture in Ethiopia

According to Hansen (2002), agriculture is the most weather dependent of human activities. Crop yield varies from season to season owing to variation in climate during the growing seasons (Bewket, 2009; Ayalew *et al*., 2012; Hadgu *et al.*, 2013; Kumar *et al*., 2013). The main weather parameter affecting crop growth are rainfall, temperature and radiation (Streenivas *et al*. 2008; Hadgu *et al*., 2014).

Therefore, having knowledge on sequences of rainfall variability, events can assist acquiring specific information for agricultural planning (Reddy *et al*., 2008; Mandal *et al*., 2013). Within variable seasonal rain fall patterns, understanding the events of the occurrence of rain features like; onset and end date of rainy season, dry spells are crucial to decrease the adverse effects and exploit opportunities (Yemenu *et al*., 2013). According to Sun *et al.* (2006), understanding how climate variability influences the yields can be helpful in designing policies that aim at reducing climate vulnerability and improving food security.

According to the study of past and future intra seasonal rainfall variability in terms of onset, end date and length of rainy season, number of rainy days, length of dry spell with in the growing period and its trend is important for agricultural purposes in the dry land area than annual and seasonal totals (Hadgu *et al*., (2013).

2.5.1. Onset of rainy season

Onset marks beginning of a season though different researchers have put it differently. For example: Stern *et al*. (1982) defined onset of a season as the date when the rainfall accumulated over 2 days is at least 20 mm and when no dry spell (exceeding 10 days) occurs within the following 30 days. Whereas, Tesfaye and Walker (2004) defined onset as the date in which 20mm or more rainfall accumulated over three consecutive rainy days after a specified date with no dry spell greater than 7 days in the next 30 days. Raman (1974) and Mamo (2005), Hadgu *et al.* (2013) and Taye *et al*. (2013) also followed the definition of Tesfaye and Walker (2004) but Hadgu *et al.* (2013) specified dry spells up to 10 days. Rita NgoziEdoga (2007) and Hulme (1987) applied the monthly minimum threshold of 60 mm and 30 mm, respectively to determine the onset of rainy season. Kowal and Knabe (1972) defined onset as the first ten-day period (decade) with more than 25 mm rain, provided that rainfall in the next decade exceeded half the potential evapotranspiration.

For *Belg* onset as indicated in Mesay (2006), rainfall total of 10 mm or more in consecutive 3 days or more with no dry spell length of 9 days or more in the next 30 days should occur with an earliest starting day first of February .

What so ever might the definition used, a study conducted in Ethiopia by Mesay (2006) noted that northern and north eastern regions have a late start of *Belg* rain in April with standard deviations of 31.9 -46.1. Another study conducted in western Amhara Region of Ethiopia revealed variability in the onset of *Kiremt* rain among stations (Taye *et al.* (2013). According to Taye *et al.* (2013) on average the *Kiremt* rain at Bahir Dar, Motta, Debre Markos and Dangla stations begins on 153^{th},151^{th}, 144^{th} and 132^{th} day of the years (DOY), respectively. On the other hand Ayalew *et al*.

(2012) reported June 15 (167 DOY) as a mean date of onset for *Kiremt* rainfall in the Amhara National Regional State.

2.5.2. End of rainy season

End of rainy season marks withdrawal of rainy season. Like onset, end of rainy season is also defined differently by different authors. For instance, Mesay (2006) used to determine end of *Belg* rain with an earliest possible day of May 1, the capacities of soils to persist precipitation with a water balance equal to zero. Whereas Tesfaye and Walker (2004) defined end of rainy season (for *Kiremt)* as the date when the available soil water content drops to 10 mm/m of the available water after September 11. Hadgu *et al.* (2013), Hadgu *et al.* (2014) and Kassie *et al*. (2014) used the same definition to determine end of rainy season. In another study, Stern *et al.* (1982), Mamo (2005), Mesay (2006) and Taye *et al*. (2013), defined as any date when water balance reaches zero after the first date of September (for *Kiremt*). FAO (1978) defined end of growing period when precipitation amount is below half of the reference evapotranspiration. For the regions except southwestern Ethiopia, Segele and Lamb (2005) defined end of rainy season for *Kiremt* as the first day of a dry-spell (<0.1mm per day) of at least 20 days duration that occurred after onset. According to the authors, this definition need to be modified when dry periods of more than 20 days extended occurred in mid-season, after which persistent rains returned. They noticed that the definition need to be complemented by the prerequisite that, if rain occurs on more than 2 days in a 30-day period after an extended dry-spell, the search for a cessation date is advanced so that a date satisfying the above basic criterion is determined from the last day of the dry-spell. Zargina (1987) and Benoit (1977) defined end date of growing season as the date in which the minimum daily rain fall threshold is 25mm in which the soil is assumed to be at field capacity (100mm). On the last day of rain that is greater than 0.5 PET, provided that the date is not proceeded by a dry spell (< 1mm average daily rainfall) or more than five days (Mubvuma, 2013). In his study end of rainy season is defined as the first dry day of the last month of the season in a period of 14 days whose cumulative rainfall total was less than 40 mm. According to Ilesanmi (1972), end of growing period is taken as the time when an accumulated 90% of the annual rainfall totals is obtained. Odekunle (2004) used the same method to determine cessation of growing period. In another study, Admassu *et al.* *(*2014) used the definition proposed by Panigrahi and Panda (2002) to determine end of rainy season. According to the authors, end of rainy season is determined using backward summation of weekly rainfall starting from 48th week until 20mm of the rainfall is accumulated.

What so ever might the definition used, a study conducted on end of rainy season in north western of Ethiopia revealed that on average the *Kiremt* rain ends on 302th, 304th, 292th, 302th and 317th DOY at Bahir Dar, Motta, Yetmen, Debre Markos and Dangla, respectively (Taye *et al*., 2013). As Ayalew *et al*. (2012) indicated, the average date of end of rainy season ranged from September 2 (246 DOY) at Mahil Meda to October 30 (304DOY) at Debark in Amhara region.

2.5.3. Length of rainy season

Length of rainy season is the duration in days between onset date and cessation date (Ayoade, 1974; Adefolalu, 1983; Madeoye, 1985; Zargina, 1987; Odekunle, 2004; Segele and Lamb 2005; Hadgu *et al*., 2013; Hadgu *et al*., 2014; Kassie *et al.*, 2014). According to Stewart (1988) and Borrell *et al.* (2003), length of growing season analysis is very important to advice farmers in selecting suitable crop variety that can be produced in specific area. Accordingly, Taye *et al.* (2013) reported that on average the *Kiremt* rainy season has length of 149,153,142,158 and 185 days at Bahir Dar, Motta, Yetmen, Debre Markos and Dangla stations, respectively in the north west of Ethiopia. In another study, Hadgu *et al.* (2013) reported that the average length of growing period in northern Ethiopia varies from 66 to 85 days depending on the location of the study area. At Mekelle, Alamata and Edagahamus, Hadgu *et al.* (2013) observed length of growing season of 85, 79 and 66 days, respectively. Models projection have also shown moderate reduction (< 20%) in the length of the growing period across Africa including Ethiopia (Thornton *et al.*, 2006).

2.5.4. Number of rainy day

Even though the smallest recorded rainfall amount is 0.1 mm, a threshold value 1mm was used to determine wet and dry days (NMSA, 2001). This is because 0.1mm rainfall has almost no effect on growth of crops (Robel *et al*., 2013). A day is considered rainy if it accumulates 1 mm or more rainfall and the opposite is true for dry day. Based on this definition, in the Tigray region of northern Ethiopia, Hadgu *et al*. (2013) counted number of rainy days for *Kiremt* season (starting from the first day of June to September 31 following the traditional classification of JJAS as *Kiremt* and found 50 days at Adigudum, 66 days at Alamata and 61 days at Mekelle. In a similar region, Seleshi and Zanke (2004) observed no-significant change in number of rainy days at Mekele for the period 1965-2002. As Ayalew *et al*. (2012) indicated, by the years of 2080s the number of rainy days will decrease in the ANRS of Ethiopia.

2.5.5. Length of dry spells

According to NMSA (2001), a day is said to be dry if it accumulate rainfall<1 mm and dry spell length is the maximum number of consecutive dry days with rainfall less than 1 mm per day exceeding 5, 7, 10, and 15 (Tesfaye and Walker, 2004). The same definition was used by Mesay (2006) to determine the dry days in rainy season.

Mesay (2006) found mean dry spell length of up to 28 days in the north western, northern and eastern parts of Ethiopia during *Belg* season. Hadgu *et al.* (2013) found dry spells of 21 days at Mekele, 26 days at Alemata and Edamame during the *Kiremt* season. In another study, Seleshi and Camberlin (2006) reported dry spell length of 20.3 days at Mekele in the northern Ethiopia and 16.2 days at Jijiga in the eastern Ethiopia.

2.6. Projected Climate Change over Ethiopia

Like in most other parts of Africa, human-induced greenhouse gas emissions would bring further change in Ethiopia's climate over the next century (Conway and Schipper, 2011). Although the level of change and associated impacts depend on the extent of emission scenarios and the climatic models used to predict the future scenarios, there are high levels of confidence that unlike temperature and rainfall is highly variable and uncertain (Sleshi and Zanke, 2004; Yimer *et al*., 2009; Conway and Schipper, 2011; Setegn *et al*. 2011; Ayalew *et al*., 2012).

In Ethiopia, a study conducted by Arndt *et al.* (2011) showed decreasing *Kiremt* and *Belg* seasons' rainfall by 20% and 5-6%, respectively by 2080s. The same study conducted by Ayalew *et al*. (2012) indicated that by the years 2080s the amount of annual rainfall and number of rainy days will decrease in the ANRS of Ethiopia. Moreover, future projection of rainfall suggests a forward shifting for *Kiremt* season, and conversely decreases for *Belg* rainfall in some places of northern

Ethiopia (Hadgu *et al*., 2014). According to the authors, in some places, the *Belg* rainfall is expected to shift from its current range of February to May to April to June. However, the pattern of its distribution, timing and intensity over the country is uncertainty (NMA 2007; Yimer *et al*., 2009; Conway and Schipper, 2011; Setegn *et al*., 2011; Ayalew *et al*., 2012)

Climatic change is also expected to alter agriculturally relevant rainfall events, thus bearing profound effects on the livelihood of farming communities (Lane and Jarvis 2007; Cooper *et al*. 2009; Sarr 2012; Kassie *et al*., 2014). Therefore, assessing the variability and expected future changes of rainfall is essential for planning and designing appropriate climate change adaptation strategies (Thornton *et al*., 2009; Kassie *et al*., 2014). More importantly, assessing climate change at local level on the basis of intra seasonal rainfall variability is essential to take advantage of changes that may lead to increased crop productivity and to buffer situations where increased stresses are likely (Thornton *et al*., 2009). This, however, depends on the availability of future climate data at local scales (Oates *et al*. 2011).

2.7. Generating Future Climate Data

General circulation models (GCMs) are currently the most widely used tools for simulating the global climate systems (Ghosh and Mujumdar, 2008). However, the out puts from GCMs are too coarse and are not readily in use at local scale (Hadgu *et al*., 2014).

Therefore the outputs from Small scaled GCMs need to be downscaled to higher and finer spatial resolutions for localized applications (Jones and Thormton, 2013; Hadgu *et al*., 2014). Although numerous downscaling tools are currently in use worldwide, the techniques that establish empirical relationships between crude scale GCMs predictors and station scale predict ants (e.g. rain fall) receive popularity in the climate community (Fowler *et al*., 2007; Green *et al*., 2011, Hadgu *et al*., 2014).

Among the GCMs, MarkSim GCM is the common and prefer able to downscale the future climate data to study the climate variability and change (Jones and Thormton, 2013; Hadgu *et al*., 2014). Unlike most statistical downscaling Models, MarkSim does not depend on long term climate data records that are not available in most developing countries. Moreover, it has the capacity to generate the minimum required climate variables (rainfall, minimum and maximum temperature and radiation) for most dynamical crop models (e.g. DSSAT). MarkSim does downscale out puts from GCMs and generate daily future data at specific station so that users can use according to their temporal and spatial interest (Jones and Thomton, 2009 and 2013). MarkSim is a third-order Markov rainfall generator (Jones *et al*., 2002; Hadgu *et al*., 2014), which has been developed over 20 years. It was not designed as a GCM downscaler, but it does now work as such, employing both stochastic downscaling and climate typing. The basic algorithm of MarkSim is a daily rainfall simulator that uses a third-order Markov process to predict the occurrence of a rainy day. A third-order model was shown to be necessary for tropical climates, whereas, according to Jones and Thornton (1993), lower-order model may suffice for temperate climates. MarkSim is valid model that does not need recalibration every time it is used, for it is calibrated over 10,000 stations worldwide clustered in to 702 climate clusters using the 36 values of monthly precipitation and monthly maximum and minimum temperatures (Joun and Thornton, 2013).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

The study was conducted in the North Eastern part of the ANRS of Ethiopia and including the North Wello and South Wello Zones (Figure 1). The study area shares administrative boundary with Tigray Regional State and North Gondar Zone in the north, with Afar Regional State in the east, Oromia Special Zone in the south and with the South Gonder and East Gojam Zones in the west.

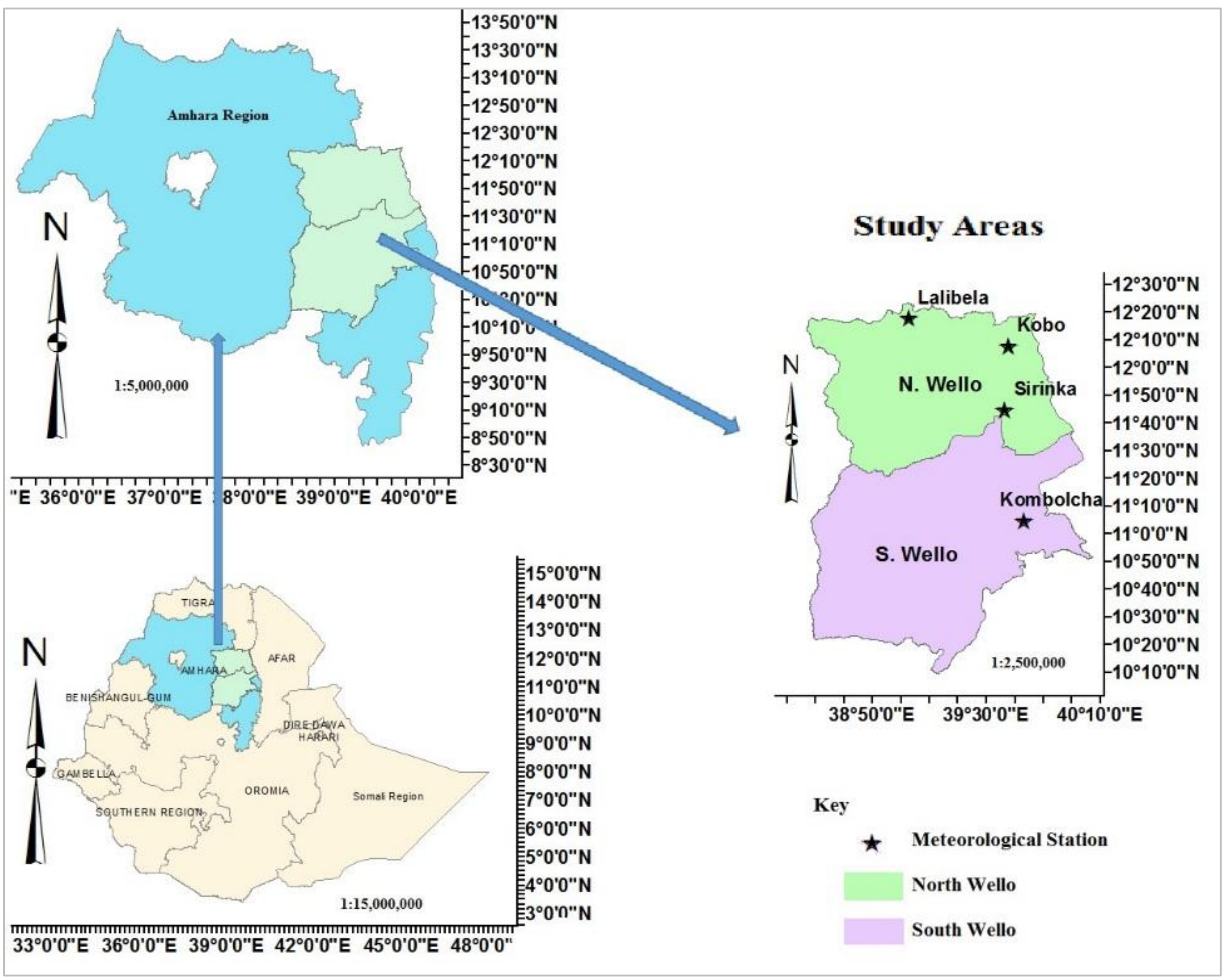

Figure 1. Location map of the study area, North Eastern Amhara, Ethiopia.

3.1.2. Climate and soil

The study area is characterized by two rainy seasons (quasi bimodal rainfall pattern). The main rainfalls is during *Kiremt* season (June- September) while the small rainfalls in *Belg* season (March-May). The study area receives a mean annual rainfall of 648.6 mm (Kobo) to 1031.1 mm (Kombolcha) with annual average maximum and minimum temperature of 14.5 ^{o}C (Lalibela) and 30.3 ^{o}C (Kobo), respectively (present study). The area is characterized by erratic rainfall and low crop productivity (Taye *et al.,* 2013). Eastern Amhara is known for its recurrent drought occurrences (Wood, 1977; Degefu, 1987; Viste *et al.,* 2012) and it is one of the most foods insecure areas in the Amhara Regional State (BoARD, 2006).

The dominant soil type in the study areas is Vertisol with different classifications: Eutric Vertisols, Calcic Vertisols and Dystric Vertisols (DSA and SCI, 2006; Tesfaye *et al*., 2011; Asrat *et al*., 2014; Feyera *et al*., 2015; Muhamed *et al*., 2015).

3.1.3. Agro ecology and farming systems

The North Eastern Amhara Region is categorized by four traditional agro-ecological zones, namely, Wurch, Dega, Woyna Dega and Kola covering 0.64, 16.25, 46.28 and 36.83% of the area respectively (Tesfaye *et al*., 2011). The major farming system in the North Eastern Amhara is mixed crop-livestock production. Productivity of land is seriously declining due to mismanagement and overutilization of natural resources (Ayalew and Selassie, 2015). As a result, the living standard of the farming community is subsistence (BoARD, 2006).

Major crops grown in the area includes cereals (teff, barely, wheat, maize, sorghum and millet), pulses (horse beans, chickpea and lentil) and oil crops (sesame, ground nuts, sunflowers and *neug*) are the major crops grown in the study area (CSA, 2011). Since the area is characterized by quasi bimodal rainfall pattern (Mesay, 2005; Segele and Lamp, 2005; Viste *et al*., 2012), some of the crops are planted and harvested in the main rainy season (*Kiremt*), and some of them in *Belg* while some others (long maturing crops) planted in the *Belg* and harvested in *Kiremt* (e.g., sorghum, millet and maize).

3.2. Data Source and Station Selection

3.2.1. Observed daily rainfall data

Long-term observed daily rainfall data from meteorological stations located in the north eastern ANRS of Ethiopia were collected from the Ethiopian National Meteorological Agency (NMA), Addis Ababa and from the archive of its branch offices at Bahir Dar and Kombolcha Directorates. Based on data availability, quality and relative length of time, four stations were selected for the study with a reasonably good geographic distribution in the study area.

Table 1. Astronomic location and rainfall database period at Kombolcha, Kobo, Lalibela and Srinka stations in the North Eastern Amhara Regional State, Ethiopia.

Meteorological Stations	Latitude (ºN)	Longitude (ºE)	Altitude (amsl)	Observation period	Missing records (%) of observation years		
					Tmax	Tmin	Rain fall
Kombolcha	11.09	39.74	1870	1992-2012	-	-	-
Kobo	12.13	39.63	1470	1992-2012	5	5	7
Lalibela	12.03	39.05	2472	1992-2012	-	-	-
Srinka	11.75	39.62	1855	1992-2012	4	4	7

3.2.2. Future daily rainfall data

Site-specific future rainfall data was downscaled from three GCMs, namely, CSIRO-Mk3-6-0, Had GEM2-ES and MIROC-ESM-CHEM under the RCP 4.5(representative concentration pathways) using MarkSim tool (Jones and Thornton 2009, 2013) for time slot centered around 2030s (2021–2040). As the difference between the four RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) is insignificant before 2050 (Chaturved *et al*., 2012) to predict precipitation and temperature, the medium range emission scenario RCP4.5 is used in the present study. Hadgu *et al*. (2014) used Marksim GCM online tool to downscale the future climate data for the same purpose but in northern Ethiopia. MarkSim is a third order Markov chain climate simulator which that is found to be suitable for tropical countries like Ethiopia (Jones and Thornton 2013). Moreover, it does not depend on long term climate data and does not need recalibration, as it is already calibrated (Jones and Thornton 2013). Marksim GCM requires geographical coordinates (latitude and longitude of the specific station) and station name to downscale and generate daily future data of a given site.

Moreover, soil data for each studied locations were obtained from previous work (FAO, 2001; DSA and SCI, 2006; Tesfaye *et al*., 2011; Muhamed *et al*., 2015; Feyera *et al*., 2015). According to the soil lab report recorded in the above authors' document, the dominated soil type for each studied station is Vertisols.

3.2.3. Data quality control

Prior to analysis, both the observed and downscaled rainfall data of all station were plotted against time (DOY format) and subjected to visual examination for the presence of discontinuities and special codes for missing values. Special codes were removed and typing errors, treated case by case using information from the day before and after the event and also by reference to nearby stations. Duplicates were removed and those identified as due to typing errors were corrected as indicated in Abbas *et al*. (2014) and Mekasha *et al*. (2014).

Finally, based on quality and relative length of time for which data is available, the four stations (Kombolcha, Kobo, Lalibela and Srinka) were selected for the study area.

Filling missing data

Missing values in the data series were filled by using Markov chain first order simulation models of INSTAT (Stern *et al.*, 2006). This is because of the fact that first order doesn`t exaggerate the result and, more-over, it give an accurate models estimates as explained in NMSA (1996b) and Stern *et al* (2006).

Outlier detection

The Turkey fence outlined in Ngongondo *et al.* (2011) was used to screen outliers using equation 3.1 as follows:

$$(Q_1 - 1.5 * IQR, Q_3 + 1.5 * IQR) \quad (3.1$$

where $Q_1$and Q_3 are lower and upper limit quartiles respectively, 1.5 represents standard deviations from the mean, and IQR represents the interquartile range. Values outside the Turkey fence were considered as outliers. Outliers were set to a limit value corresponding to ±1.5 × IQR.

Homogeneity test:

Homogeneity test of rainfall data for each studied stations in the North Eastern Amhara is carried out using RClimDex software.

3.3. Definition of Intra Seasonal Rainfall Indices

At each of the selected station, the past and future intra seasonal rainfall were analyzed in terms of onset of rainy season; end of rainy season; seasonal total rainfall (mm); length of rainy season; length of dry spell; coefficient of variation and rainfall anomaly.

3.3.1. Onset of rainy season

the onset of rainy season was determined as the date when 20 mm or more rainfall accumulated over three consecutive rainy days after a starting date (1st of June for the *Kiremt* season and 1st of February for the *Belg* season*)* with no dry spell length greater than 7 days in the next 30 days as used in Tesfaye and Walker (2004) and Mesay (2006). INSTAT 3.36 software is used to compute start date of growing season for each studied stations.

3.3.2. End of growing season

On the other hand, the end of growing season was mainly dictated by the stored soil water and its availability to the crop after the rain stops. In this study, the end of the rainy season was defined as any day after 1st of September for *Kiremt* and 1st of May for *Belg* seasons when the soil water balance reaches zero (Stern *et. al*, 1982). Since the dominant soil for all locations studied is Vertisols with high clay content (>50%), a 100 mm/meter of the plant available soil water and site specific daily reference evapotranspiration (ETo) values were considered.The same method was used by several authors to determine end date of growing season (Mamo, 2005; Mesay, 2006; Feyera, 2013; Taye *et al.*, 2013; Feyera *et al*., 2015). In addition to Soil water holding capacity for each studied stations, site specific daily Evapotranspiration (ETo) is computed enable to compute EOS for each station using INSTAT v. 3.36 software. Hence, site specific daily ETo data is computed under sub section 3.5 below using Hargreaves and Samani model**.** All the procedures applied to compute daily ETo are discussed under the sub section analysis of evapotranspiration (3.5).

3.3.3. Length of growing period

Length of *Kiremt* and *Belg* growing season was determined as the difference between the end and onset of rainy season (Mamo, 2005; Mesay, 2006; Feyera, 2013; Hadgu *et al*., 2013; Hadgu *et al*., 2014; Feyera *et al*., 2015).

3.3.4. Number of rainy and dry days

Even though the smallest recorded amount of rainfall is 0.1 mm, a threshold value of 1mm was used to define days as wet or dry because 0.1mm of rainfall value almost has no effect on growth of crops (Robel *et al*.,2013). Thus, in the current study, number of rainy and dry days were determined by counting all days with rainfall $\geq$1.0mm as rainy and those days with $<$ 1.0mm as dry days respectively as outlined by (NMSA, 2001). Different researchers used the same definition (Segele and Lamb, 2005; Mesay, 2006; Hadgu *et al*., 2013).

3.3.5. Rainfall totals

Annual and seasonal rainfall totals were determined as sum of rainfall of each day with greater or equal to 1 mm (NMSA, 2001; Segele and Lamb, 2005; Mesay, 2006; Hadgu *et al*., 2013) for the specified period.

3.3.6. Dry spell probability

The dry spell probabilities were determined as consecutive number of days with rainfall less than 1 mm per day exceeding 5, 7, 10 and 15 consecutive days. Dry spell length was analyzed by Markov Chain analysis (Stern *et al*., 2006; Sreenivas *et al*., 2008; Stern and Cooper, 2011) using INSTAT v3.36 software. The probability of maximum dry spells on calendar and on crop calendar basis at lengths of 5, 7, 10 and 15 days were computed using Markov chain model to obtain an overview of dry spell risks and to study dry spells risk in the growing season, respectively.

3.4. Variability Analysis

The past and future intra seasonal rainfall indices were analyzed using the coefficient of variation (CV), standard deviation (SD), and mean, median

Where CV can be computed as:

$$CV\% = \left(\frac{SD}{\overline{\overline{X}}}\right) * 100 \qquad (3.15)$$

Where x and δ are the average and standard deviation of rainfall, respectively over the given period. According to Hare (1983), CV (%) values are classified as follows: < 20% as less variable, 20- 30% as moderately variable, and > 30% as highly variable.

On the other hand, standard deviation is computed as the square root of variance. Using the classification of Reddy (1990), the stability of rainfall is examined as follows: when standard deviation <10 as very high stability, 10-20 as high stability, and 20-40 as moderate stability and >40 as less stability. Where SD can be computed as:

$$SD = \sqrt{\left[\sum_{i=1}^{n} \frac{1\left(X_i - \overline{X}\right)^2}{n}\right]} \qquad (3.16)$$

Rainfall anomaly: Rainfall anomaly was used to examine the nature of rainfall over the period of observation and to determine dry and wet years in the record.

Rainfall anomaly (Z) was calculated as:

$$Z = \frac{(X - \mu)}{\delta} \tag{3.16}$$

where, x is the seasonal total rainfall of a particular year; μ is mean of the observation and δ is the standard deviation of the observation. Based on Z values, drought severity classes are given as extreme drought (*Z* < -1.65), severe drought (-1.28 > *Z* > -1.65), moderate drought (-0.84 > *Z* > -1.28), and no drought (*Z* > -0.84) (McKee, 1993). The same method was used by Ayalew *et al.* *(*2012) and Hadgu *et al*. (2013) to identify dry and wet years in their study.

3.5. Analysis of Reference Evapotranspiration (ETo)

3.5.1. Computing daily ETo: Using Hargreaves and Samani model

Different researchers used Hargreaves and Smani (HS) model to estimate ETo where no full data is available (Allen *et al*., 1998; Hargreaves and Samani, 1982; Araya and Stroosnijder, 2011). The HS model is calibrated and evaluated against Penman Monthieth model to the study area before it is applied to estimate ETo for the selected stations (Kombolcha, Srinka, Lalibela and Kobo). The full steps of calibration and evaluation is stated below in detail.

Calculation of Reference Evapotranspiration (ETo)

FAO PenmanMonteith model

Daily Reference Evapotranspiration (ETo) is an important tool in determining the water needs of different crops (Allen *et al*., 1998; Shahidian *et al*., 2013). The United Nations Food and Agriculture Organization (FAO) has adopted the Penman-Monteith method as a global standard for estimating ETo from four meteorological data (temperature, wind speed, radiation and relative humidity) (Allen *et al*., 1998). Similar to other workers (e.g., Araya and Stroosnijder, 2011) CROPWAT 8.0 software was to calculate ETo using the Penman Monteith method for this study.

Hargreaves and Samani (HS) method

The Penman Monteith equation is generally considered as the most reliable, in a wide range of climates and stations, because it was based on physical principles and considers the main climatic factors, which affect evapotranspiration (Allen *et al*., 1998; Shahidian *et al*., 2013). However, there are limitations to use it in estimating ETo. Among the most common limitation is the number of climate variables used to run the model. Particularly, in most developing country, like Ethiopia, the number of meteorological stations where all the required climate parameters are observed is limited and the number of stations where reliable data for these parameters exist are very few (Hargreaves and Samani, 1982; Allen *et al*., 1998; Araya and Stroosnijder, 2011; Mubvuma, 2012).

These and other limitations created interest and has encouraged development of practical methods, based on a single or reduced number of weather parameters for computing ETo (Hargreaves and Samani, 1985; Shahidian *et al*., 2013). Among the reduced set equations, temperature based equations (Thornth waite 1948; Blaney Griddle 1950; Hargreaves and Samani, 1985) are the most common equations to estimate ETo on different time basis according to the researcher interest (Shahidian *et al*., 2013; Jensen, 1985). According to Jensen (1985), about 80% of ETo is explained by temperature alone.

Different reports revealed that HS equation is the best method after FAO Penman Monteith equation to estimate ETo (Murugappan *et al*., 2005; Lopez-Urrea *et al*., 2006; Moeletsi, 2010; Araya and Stroosnijder, 2011; Shahidian *et al*., 2013). In the current study, HS equation was applied to estimate ETo for all selected stations in the study area. Araya and Stroosnijder (2011) used the same method to estimate ETo in the orthern region of Ethiopia with the same procedure.

The HS equation (Hargreaves and Samani, 1985) in its original form is computed as:

$$ET_o = 0.0023 * (T_{mean} + 17.8)(T_{\max} - T_{\min})^{0.5} Ra \tag{3.5}$$

Where ETo is reference evapotranspiration [mmd^{-1}], T_{mean} *is* average air temperature , T_{max} and T_{min} are maximum and minimum air temperatures (^{o}C), respectively and R_a *is* extraterrestrial radiation [$MJm^{-2}d^{-1}$].

The extraterrestrial radiation, Ra, for each day of the year and for different latitudes was estimated from the solar constant, the solar declination and the time of the year as follows:

$$R_a = \frac{24(60)}{\pi} G_{SC} d_r \left[\omega \sin(\phi)\sin(\delta) + \cos(\delta)\sin(\omega_s)\right] \tag{3.6}$$

where R_a- Extraterrestrial radiation [MJm^{-2}day^{-1}], G_{sc}- Solar constant: 0.0820[MJm^{-2}min^{-1}], d_r −Inverse relative distance Earth-Sun, ∅-Sunset hour angle [rad], δ- Latitude [rad] and ω_s-Solar declination [rad]

The inverse relative distance Earth-Sun, d_r and the solar declination, δ are calculated using:

$$d_r = 1 + 0.033\cos\left[\frac{2\pi}{366} J\right] \tag{3.7}$$

$$\delta = 0.409\sin\left[\frac{2\pi}{365} J - 1.39\right] \tag{3.8}$$

Where J is the number of the day in the year between 1(January) and 365 (31 December).

$$\omega_s = Arc\cos\left[-\tan(\varphi)\tan(\delta)\right] \tag{3.9}$$

3.5.2. Calibration of HS model against FAOPM model

Different researchers strongly recommended that simple local calibration need to be done when there is a need of using the HS equation in different areas of its original place where the models was calibrated on different time basis (Moeletsi, 2010; Araya and Stroosnijder, 2011; Mubvuma ; 2012; Shahidian *et al*., 2013). From the previous reports done at different areas, HS model tends to under or overestimate ETo (Reis *et al*., 2007; Rahimkoob, 2008; Moeletsi, 2010; Shahidian *et al*., 2013). Because of the tendency of underestimation or overestimation ETo value in the current study, it was learned that original HS equation cannot be applied to the study area without calibration.

Therefore, calibration had to be carried out in order to use it for ETo estimation as reported in other studies (Moriasi *et al.*, 2007; Araya and Stroosnijder, 2011; Moeletsi, 2010; Shahidian *et al.*, 2013; Shahidian *et al*., 2013). Allen *et al*. (1998) recommends HS local calibration on monthly or annually basis and several authors used monthly average ETo data to calibrate the model (Moeletsi 2010; Shahidian *et al.*, 2013; Valero *et al.*, 2013). In the current study, monthly averaged ETo data is used to calibrate the HS model. Therefore, five (2005-2009) and three (2010-2012) years data were used to calibrate and validate the model, respectively. Calibration was carried out at Kombolcha weather station where daily maximum and minimum temperature, daily relative humidity, daily sunshine hours and daily wind speed data were available and averaged on monthly basis. Monthly averaged ETo for the study period was calculated with the PM and HS methods for calibration and validation purpose.

A linear regression equation, established with PM ETo values plotted as the dependent variable and values from the HS equation plotted as the independent variable, was used to generate calibration coefficients (Shahidian *et al*., 2013; Erickra, 2014). The intercept, *a*, and calibration slope, *b*, of the best fit regression line, were then used as regional calibration coefficients (Moriasi *et al*., 2007; Shahidian *et al*., 2013). The assumption to use linear regression was that all the errors are from the prediction model and the PM was free from error. Ngongondo *et al*. (2011) and Shahidian *et al*. (2013) used the same assumption while they used linear regression method to calibrate and evaluate HS against PM. In the case of Ethiopia, Araya and Stroosnijder (2011) used the same method and procedure to calibrate and validate HS model.

The linear regression equation was computed as:

$$ET_{oPM} = a + b * ET_{oHS} \text{ (mm per day)} \quad (3.10)$$

Where $ET_O PM$ is ETo from PM equation used as dependent variable in mm/day, $ET_O HS$ is ETo from HS equation used as independent variable in mm/day , a is intercept and b is slope of the regression line.

3.5.3. Evaluation of the performance of HS model

Evaluation of the performance of a calibrated models is a very important step in modelling process (Moriasi, 2007; Araya and Stroosnijder, 2011; Moeletsi, 2010; Shahidian *et al*., 2013). Among the methods to validate the model, the mean bias error (MBE), root mean square error (RMSE), the coefficient of determination (R^2) and d (index of agreement) are the common ones. In the same way Ngongondo *et al*. (2011), Mubvuma (2012), Valero *et al*. (2013) and Lima *et al*. (2013) also used these statistical methods to evaluate HS model. Along with Kombolcha, Srinka weather station was also used for model evaluation using the 2010-2012 data.

The range of R^2 lies between 0 and 1 which describes how much of the observed dispersion is explained by the prediction. A value of R= 0 means no linear correlation at all, whereas the value of R= 1 means that the dispersion of the prediction is equal to that of the observation. The fact that only the dispersion quantified is one of the major drawbacks of R^2 if it is considered alone. A model which systematically over or under predicts all the time could still result in good values close to 1.0 even if all predictions were wrong (Krause *et al*.,2005; Moriasi *et al*., 2007). According to Moriasi *et al*. (2007), this might be because of oversensitive for outliers and insensitive for additive and proportional differences between observed and predicted data sets. Hence other commonly used methods such as RMSE, MBE and d-index were included to calibrate and evaluate the performance of the model against the standard model. The RMSE was calculated as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[ET_{OHS} - ET_{OPM}\right]^2} \quad \text{(mm per day)} \tag{3.11}$$

RMSE assesses the model performance based on observed and estimated variables with the best estimates having RMSE ≅ 0 (Jacovites and Kontoyiannis, 1995). The MBE was computed as:

$$MBE = \frac{1}{n}\sum_{1=i}^{n}\left[ET_{OHS} - ET_{OPM}\right] \quad \text{mm per day} \tag{3.12}$$

Where n is the number of samples (number of months), ET_{OHS} is estimated values from HS equation in mm/day, ET_{OPM} is observed values from PM equation in mm/day.

The MBE provides an overall average of the error, accounting for under and over estimates of ETo by including the sign of the error (Subburayan *et al*., 2011). According to the authors, negative sign indicates under estimation and positive sign indicates overestimation. Mean Bias Error ≅ 0 represents best estimates of ETo by the model (Jacovides and Kontoyiannis, 1995). The index of agreement (d) was computed using the following equation

$$d = 1 - \frac{\sum_{i=1}^{n}\left[ET_{OHS} - ET_{OPM}\right]^2}{\sum_{i=1}^{n}\left[\left|ET_{OHS} - \overline{ET_{OPM}}\right| + \left|ET_{OPM} - \overline{ET_{OPM}}\right|\right]^2} \tag{3.13}$$

Where $\overline{ET_{OPM}}$ is average ETo value from PM in mm/day.

The range of d is similar to R^2 and lies between 0 that indicates no correlation while values close to 1 indicates perfect fit (Willmot, 1982). Various researchers used this method to evaluate the performance of a model (Krause *et al*., 2005; Mamo, 2005; Shahidian *et al*., 2010).

From the statistical summary information provided in Table 2, it is clear that the HS equation cannot be applied without calibration to estimate ETo for given site. It is clearly seen that R^2 alone cannot be used for evaluating model calibration and evaluation.

Finally, the calibrated HS equation used to estimate ETo for this study was the following:

$$ET_{OHSc} = (-0.3092) + (0.9211) * ET_{OHSO} \quad \text{(mm per day)} \tag{3.14}$$

Where ET_{OHSc} is ETo values from the calibrated HS equation and ET_{OHSo} = ETo values from HS equation before calibration.

3.6. Trend Analysis

For all rainfall indices, trend test was carried out using the non-parametric Mann-Kendall's trend test which is less sensitive to outliers and test for a trend in a time series without specifying whether the trend is linear or non-linear (Partal and Kahya, 2006; Yenigun *et al.,* 2008; Hadgu *et al.,*2013). The Mann-Kendall's test statistic was given as:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \text{sgn}(X_j - X_i) \tag{3.17}$$

Where S was the Mann-Kendal's test statistics; x_i and x_j were the sequential data values of the time series in the years i and j (j>i) and N was the length of thfe time series. A positive S value indicates an increasing trend and a negative value indicates a decreasing trend in the data series.

The sign function was computed as:

$$\mathrm{Sgn}(x_j - x_i) = \begin{cases} +1 \text{ if } (x_j - x_i) > 0 \\ 0 \text{ if } (x_j - x_i) = 0 \\ -1 \text{ if } (x_j - x_i) < 0 \end{cases} \tag{3.18}$$

The variance of S, for the situation where there may be ties (that is, equal values) in the x values is given by:

$$\mathrm{Var}(S) = \frac{1}{18}\left[N(N-1)(2N+5) - \sum_{i=1}^{m} t_i\,(t_i - 1)(2t_i + 5)\right] \tag{3.19}$$

Where *m* was the number of tied groups in the data set and t_i was the number of data points in the i^{th} tied group. For n larger than 10, Z_{MK} approximates the standard normal distribution (Partal and Kahya, 2006; Yenigun *et al*., 2008) and computed as follows:

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{var}(s)}}\ if S > 0 \\ 0 if S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{var}(s)}}\ if S < 0 \end{cases} \tag{3.20}$$

The presence of a statistically significant trend was evaluated using the Z_{MK} value. In a two-sided test for trend, the null hypothesis Ho was accepted if $|Z_{MK}| < Z_{1-\alpha/2}$ at a given level of significance. $Z_{1-\alpha/2}$ was the critical value of Z_{MK} from the standard normal table. For example: for 5% significance level, the value of $\mathbf{Z_{1-\alpha/2}}$ is 1.96. A positive value of Z_{MK} indicates an increasing trend while a negative value indicates a decreasing trend. In the present study, the significance of observed change is examined at $p \leq 5\%$ significance level. Therefore taking 0.05 significance level as reference, the significance levels 0.01 and 0.001 are considered in the present study.

The rate of change is computed using Sen's slope estimator, which can be used with missing data and remain unaffected by outliers or gross errors (Karpouzos *et al.*, 2010), is used to depict changes per year as outlined in Sen. (1968), Partal and Kahya (2006) and Karpouzos *et al*. (2010).

Sen's slope estimator was computed as:

$$T_i = \frac{X_i - X_k}{J - K} \; for i = 1,2,3...N \tag{3.21}$$

Where X_j and X_k are considered as data value at time k (j>k) correspondingly. The median of these N values of T_i is represented as Sen's estimator of slope given by

$$Q_i = \begin{cases} T_{\frac{T+1}{2}} ....N = odd \\ \frac{1}{2}\left\{ T_{\frac{N}{2}} + T_{\frac{N+2}{2}} \right\} ....N = even \end{cases} \tag{3.22}$$

Sen's estimator was computed as Q_{med}=T (N+1)/2 if N appears odd and it is considered as Q_{med}= (TN/2+T (N+2)/2 if N appears even. At the end, Q_{med} was computed by a two sided test at 100 (1-α) % confidence interval and then a true slope was obtained by the non-parametric test. Positive value of Q indicates an upward or increasing trend and negative value shows decreasing trend and if the values are zero, it shows the data are fluctuate around the mean. MAKESENS_1_0 excel based templet software is used to carry out the computations.

4. RESULTS AND DISCUSSIONS

The analysis of past and future rainfall variability and trend is conducted after the quality control is done, missed data is filled. The RClimDex software indicated that the rainfall data did not show heterogeneity during 1992-2012 at Kombolcha, Kobo, Lalibela and Srinka stations in study area (The Appendix Figure 1. All the four panels showed the original daily precipitation pattern series are homogeneous for the period of study. Hence, the rainfall data is used for further analysis in the present study.

Calibration and validation result of HS model

The result of calibration and validation of HS model against of Penman Montheith is presented in Table 2. Before calibration is done, the comparison of ETo values computed by HS model against Penman Montheith model revealed that the HS Model needs local calibration. The values of index of agreement (d), root mean square error (RMSE) and mean bias error (MBE) showed the model needs calibration to local area. The calibration and evaluation result of the HS model against FAO Penman Montheith model in Table 2 indicated that the model can be used to compute ETo in the study area. As reviewed in detail under section 3, HS model can be applied unless it is calibrated locally

Table2. Summary statistics of the linear regressions between monthly-averaged ETo calculated with the Penman Monteith equation (EToPM) and the Hargreaves and Samani equation (EToHS) for the period 2005-2012 at two stations.

HSc= calibrated HS equation, HSo= original HS equation.

Stations	project	Period	R^2	d	RMSE	MBE	Remark
Kombolcha	Before	2005-2009	0.94	0.67	0.72	0.70	Not accept able
Kombolcha	Calibration	2005-2009	0.94	0.97	0.10	0.01	Acceptable
Kombolcha	Evaluation	2010-2012	0.97	0.97	0.10	0.09	Accept able
Srinka	Evaluation	2010-2012	0.84	0.93	0.19	0.03	Accept able

Then the final calibrated linear regression model used to compute ETo at studied station is

$$ET_{oCHS} = (-0.3092) + (0.9211) * ET_{oHSO} \quad \text{(mm per day)}$$

Where EToCHS ≅ EToFAOPM

4.1. Variability and Trends of Observed Rainfall

4.1.1. Annual rainfall

As indicated in Table 3, the North Eastern Amhara Region received long-term mean annual rainfall of 882.3 mm ranging from 648.6 mm at Kobo to 1311.1 mm at Kombolcha during the period of study (1992-2012). The results of the present study are in agreement with the previous studies of Bewket (2009) and Ayalew *et al.* (2012) who reported similar values at Kombolcha, Lalibela and Srinka weather stations for the period 1978-2009. The coefficient of variation observed in the present study also ranged from 12% at Labella and Kombolcha to 15% at Kobo (Table 3) which can be classified as less variable (< 20%) according to the classification of Hare (1983). On the other hand, according to Reddy (1983), the stability of the observed annual rainfall were less at all stations studied (SD= 94mm-130.5mm)

Table3. Descriptive statistics of observed annual rainfall totals at four stations in the North Eastern Amhara Regional State (1992-2012).

Stations	Statistics				
	Max (mm)	Mean (mm)	Min (mm)	CV (%)	SD (mm)
Kombolcha	1311.1	1031.1	814	12	124
Kobo	844.9	648.6	457.2	15	94.0
Lalibela	980.1	826.8	516.6	12	102.3
Srinka	1308.9	1022.5	762.7	13	130.5

4.1.2. Seasonal rainfall totals variability

The contribution of seasonal *Kiremt* rainfall to the respective annual total rainfall varied from 60% at Srinka to 76% at Lalibela during the period of 1992-2012. A comparable study result of main (*Kiremt*) rain season contribution to the annual rainfall totals was reported by Ayalew *et al*. (2012)

in the ANRS with the range of 55% at Srinka to 84 % at Bahir Dar for the period 1979-2008. In the present study, the total seasonal *Kiremt* rainfall varied from 205.9 mm at Kobo to 950.3 mm at Kombolcha (Table 4). The CV for the seasonal *Kiremt* rainfall varied from 14% at Lalibela to 22% at Kobo. It is only at Kobo that the CV exceeded 20% indicating that most parts of the north eastern Amhara experienced less variable *Kiremt* season rainfall. Similar results were also reported by Zanke and Seleshi (2004), Segele and (2005), Ayalew *et al*. (2012) and Hadgu *et al*. (2013) in the north and north eastern parts of Ethiopia. The observed SD values showed that the past *Kiremt* rainfall was less stability (SD= 85mm at Kobo-134mm at Kombolcha). This less stability shows that the seasonal *Kiremt* rainfall totals were not easily predictable and resulted in difficulty to take decision regarding to rain fed crop production during the study period.

Table4. Observed seasonal *Kiremt* and *Belg* rainfall totals at four stations in the North Eastern Amhara, Ethiopia, during the study period (1992-2012).

stations	statistics					
	Max (mm)	Min (mm)	Mean (mm)	SD (mm)	CV (%)	CT (%)
			Kiremt			
Kombolcha	950.3	278.8	649.5	134	20.8	64.2
Kobo	550.2	205.9	387.1	85	22	60.0
Lalibela	793.6	396.1	626.2	89.0	14	75.7
Srinka	846.5	383.4	597.6	106.8	18	59.6
			Belg			
Kombolcha	471.0	49.6	264.4	93	35	26.1
Kobo	276.1	89.1	172.4	49	28.4	26.6
Lalibela	233.8	51.3	150.5	58	39	18.0
Srinka	477.2	61.0	271.8	103.0	38	26.6

Where SD is standard deviation, CV is coefficient of variation and CT is contribution of seasonal totals

On the other hand, the contribution of seasonal *Belg* rainfall to the annual total varied from 18.0% at Lalibela to 26.6% at Kobo and Srinka *on par* (Table 4). This indicates that the contribution of the seasonal *Belg* rainfall to the annual total is less than half of the contribution of the seasonal *Kiremt* rainfall. In line of the present study, NSMA (2005) also noted that, over the north, northeastern and eastern parts of Ethiopia, the contribution of seasonal *Belg* rainfall to the annual total range from 5 to 30%. In a similar study, Taye *et al*. (2012) also found 20% - 30% contribution of the seasonal *Belg* rainfall in the same region during 1979-2008.

The observed mean seasonal *Belg* rainfall totals were ranged from 150.5mm at Kobo to 271.8mm at Srinka stations.in line with present study result, Bewket (2009) reported a comparable mean *Belg* rainfall of 136 mm at Lalibela and 230 mm at Kombolcha for the period of 1975- 2003. Unlike the observed seasonal *Kiremt* rainfall, the seasonal *Belg* rainfall of the present study showed marked variability (Table 4) with CV value of 28.4% at Kobo to 39% at Lalibela with the SD value of 49.0 mm and 58 mm, respectively. This implies that the seasonal *Belg* rainfall was characterized by high variability according to the classifications given in Hare (1983). Similar high seasonal *Belg* rainfall variability was also reported by Ayalew *et al*. (2012) over the Amhara Region compared to the *Kiremt* and annual total rainfall during 1979-2008. The observed less stability and high variability of *Belg* rainfall totals indicate that the rainfall was not dependable and easily predicable. This indicates that rain fed crop production have been challenged in the North Eastern Amhara during 1992-2012.

4.1.3. Seasonal rainfall anomaly

The *Kiremt* rainfall anomaly showed that more than half (51 %) of the observation years were experiencing an amount lower than the long term mean. Depending on the stations studied, the years 2002 and 2009 were found to have *Kiremt* rainfall below 1.5 times the SD of the mean of the study period (1992-2012), and these years can be classified as years of sever to extreme drought, according to the index classification used in Taye *et al*. (2013) and Hadgu *et al*. (2012). In line with the present study result, Viste *et al*. (2012) indicated that 2002 and 2009 years were found as severe to extreme *Kiremt* drought years over Ethiopia. Over all the studied stations, the years 1992, 1997, 2000, 2002, 2009 and 2011 years were characterized by *Kiremt* rainfall below the mean of the study period (Figure 2) and could be classified as moderate to severe drought years. On the other hand, an average 49% of the years have been experienced rainfall above the long term mean of the study period (Figure 2).

Accordingly, in the present study, the years 1993, 1995, 1996, 1997 and 2012 are observed having a *Kirem*t rainfall total above the long term mean of the study period across all the studied stations. The present study result implies that the *Kiremt* rainfall in the North Eastern Amhara Region was characterized by dry and wet conditions (Figure 2). Clearly, one can understand that rain fed crop production in the study area have been challenged by risk of dry years during the study period. In agreement with the present study, Bewket (2009), Ayalew *et al.* (2012), *Viste et al. (2012*) noticed that the rain fed agriculture was highly at risk in the North Eastern Amhara Region.

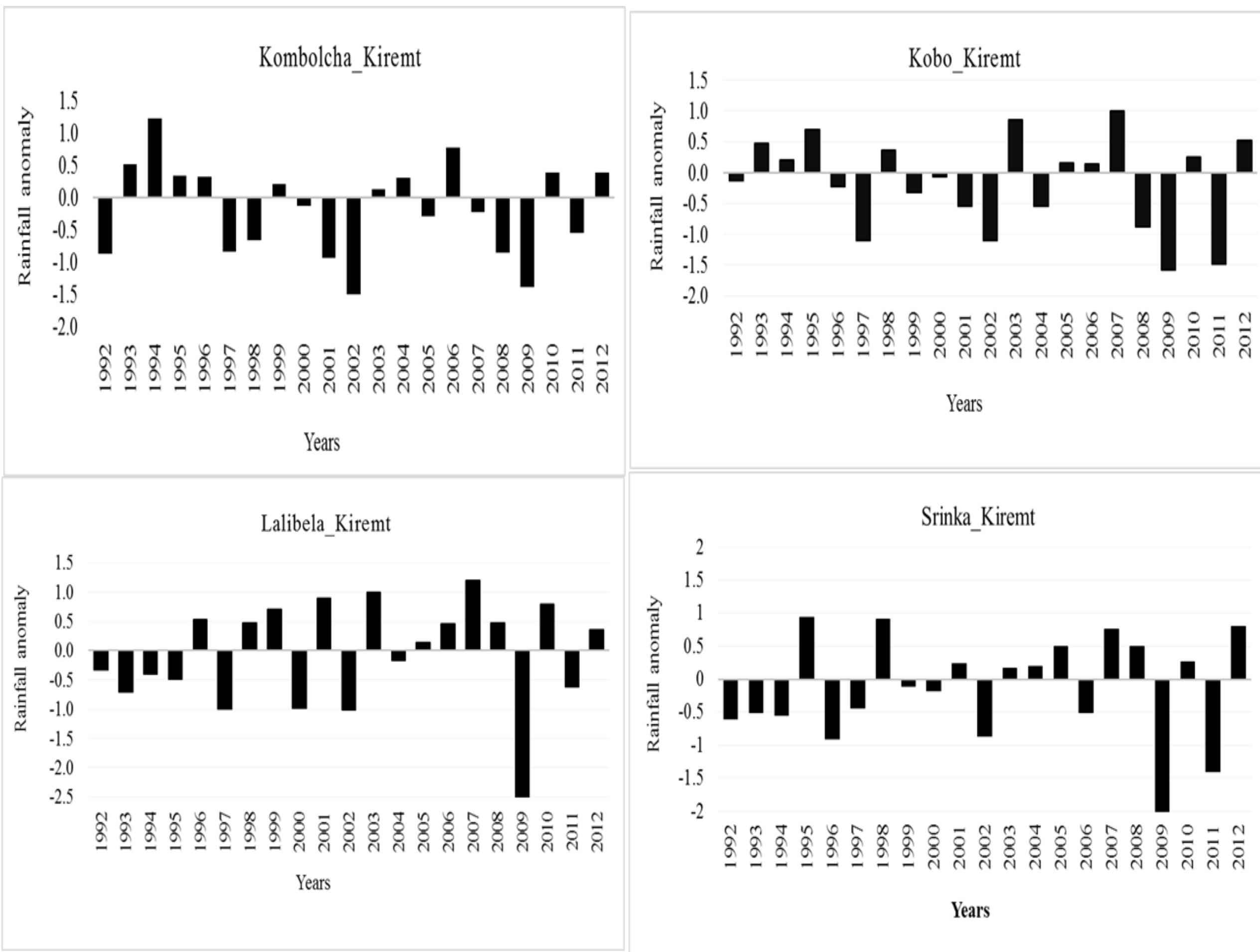

Figure 2. Observed *Kiremt* season rainfall anomalies at four stations in the North Eastern Amhara Region, Ethiopia, during 1992-2012.

On the other hand, the analysis of the seasonal *Belg* rainfall anomaly revealed that 50% of the years in the study period (1992-2012) have been experienced rainfall below the mean (Figure 3). Depending on the stations studied, the years 1992, 1994, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2007, 2008, 2009 and 2011 were the years with *Belg* season rainfall values below the long-term mean of the study period. Moreover, the observation years 1992, 1999,2000,2008,2009 and 2011 were identified being dry years at all stations in the study area. In line with the present study result, Viste et al. (2012), after thorough examination of 1972-2011 rainfall, reported that North Eastern Ethiopia experiencing sever to extreme drought during these years.

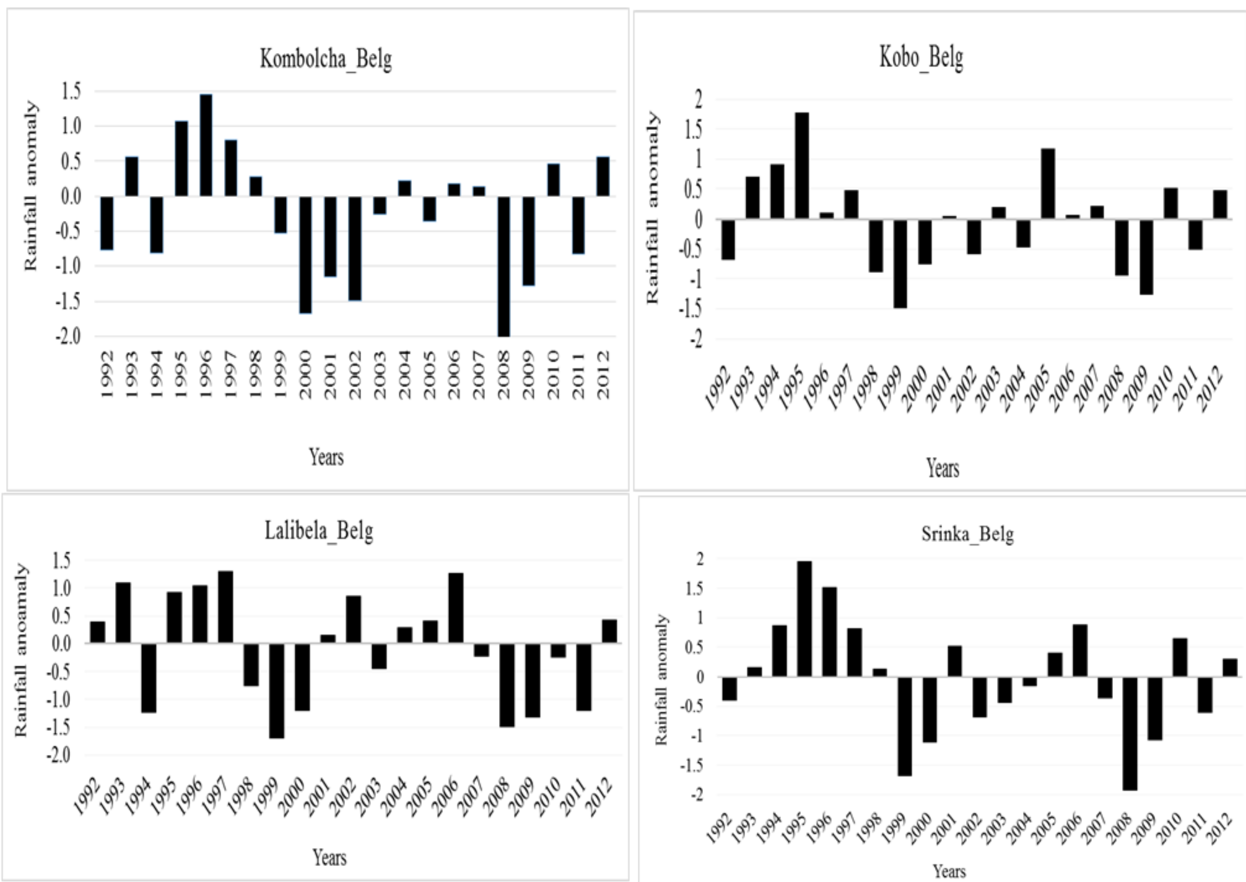

Figure 3. Observed *Belg* season rainfall anomalies at four stations in the North Eastern Amhara Region, Ethiopia, during 1992-2012.

In the present study, the observed *Belg* season rainfall anomaly showed that 50% of the years experienced rainfall above the mean of the study period. At all studied stations, the years, 1993, 1995, 1996 and 1997 were found to have *Belg* rainfall values above the mean of the study period

(1992-2012). Depending on the studied stations, the years 1994, 1998, 2001, 2003, 2005, 2006, 2007, 2010 and 2012 were also observed to have seasonal *Belg* rainfall above the mean of the study period. However, the years 1995 at Kobo and Srinka, 1996 at Kobolcha and Srinka, were marked by high rainfall values of 1.5 times the SD above the mean of the study period making them the wettest years of the study period.

4.1.4. Seasonal rainy and dry days variability

The number of seasonal *Kiremt* and *Belg* rainy days and dry days at four stations in the North Eastern Amhara Region is depicted in Table 5. The observed number of seasonal *Kiremt* rainy days (NRD) varied from 36 days at Kobo to 77 days at Lalibela. On average, there were more NRD in a year at Lalibela (Table 5). The observed CV values also showed that there was more variability in the NRD at Kobo and conversely, less at Lalibela than the other stations studied during 1992-2012. On the other hand, the observed number of *Kiremt* dry days (NDD) varied from 45 days at Kobo to 85 days at Lalibela, respectively. On average, there were more NDD in a year at Kobo than the rest of the studied stations (Table 5). The observed CV of *Kiremt* NDD in the present study also indicated that there was relatively more inter annual variability of seasonal *Kiremt* NDD at Kobo and Kombolcha. Zanke and Seleshi (2004) reported comparable result in NDD for *Belg* and *Kiremt* seasons at Kombolcha for the study period of 1965-2002.

On the other hand, the observed *Belg* NRD varied from 8 days at Lalibela to 48 days at Kombolcha during 1992-2012 (Table 5). There were, on average, more *Belg* season NRD in a year at Kobo than the rest of the stations studied. The observed CV of *Belg* season NRD also showed that there was moderate to high inter annual variability in the NRD at all the studied stations with the smallest values at Kobo (25 %) and the highest values at Srinka (33%). This indicates that the NRD in the past *Belg* season was less dependable in the study area. Moreover, the observed seasonal *Belg* NDD varied from 72 days at Kombolcha to 112 days at Lalibela. Moreover, the present study has shown that the number of rainy days was more variable during the *Belg* season than during the *Kiremt* season, and the number of dry days was less variable than the number of rainy days in both seasons.

Table 5. Number of rainy days (NRD) and dry days (NDD) during seasonal *Kiremt* and *Belg* at four stations in North Eastern Amhara, Ethiopia, during 1992-2012.

Seasons	Indices	Statistics	Kombolcha	Kobo	Lalibela	Sirinka
Kiremt	NRD	Maximum (days)	69	65	77	68
		Mean (days)	56	51	65	57
		Minimum (da ys)	42	36	55	46
		CV %	13	18	10	12
		SD (days)	7	9	6	6
Belg		Maximum (days)	48	40	37	34
		Mean (days)	28	30	23	26
		Minimum (days)	10	16	8	10
		CV %	31	25	29	33
		SD (days)	9	7	7	9
Kiremt	NDD	Maximum (days)	80	85	68	76
		Mean (days)	66	71	57	65
		Minimum (days)	52	57	45	54
		CV %	12	12	11	10
		SD (days)	7	9	6	6
Belg		Maximum (days)	111	105	112	111
		Mean (days)	92	90	98	94
		Minimum (days)	72	80	83	76
		CV %	10	8	7	10
		SD (days)	9	7	7	9

NB: NRD is Number of Rainy Days, NDD is Number of dry days, CV is Coefficient of Variation and SD is Standard Deviation.

From agricultural point of view, high inter annual variability in the number of rainy days shows less dependability of the rains for planning activities which may lead to crop failures. Particularly, the high variability of rainy days for the *Belg* season could be a great problem for farmers who lack instruments to quantify rainfall amount but rather depend on number of rainy days to plan cropping calendar.

4.1.5. Length of growing seasons (LGS)

4.1.5.1. Length of *Kiremt* growing season

Summary statistics for the past length of *Kiremt* growing season (LGS) during 1992-2012 at four stations in the North Eastern Amhara is depicted in Figure 4 and Appendix Table 1. From the present study, planting earlier than 03July month (DOY 185) is possible once in four years time at Kombolcha and Kobo whereas, planting earlier than 28 June (DOY 180) and 01 July (DOY 183) is possible only once in four years at Lalibela and Srinka. On the other hand, planting earlier than 10July (DOY192), 12July (DOY194), 08July (DOY190) and 12July (DOY194) is possible three times in four years at Kombolcha, Kobo, Lalibela and Srinka. During the study period, the median SOS of *Kiremt* growing season were observed being DOY187 (Jul-5), DOY190 (Jul-8), DOY187 (Jul-5) and DOY187 (Jul-5) for Kombolcha, Kobo, Lalibela and Srinka, respectively. In line with the present result, Ayalew *et al*. (2012) also found DOY189 (July-9) and DOY186 (July-4) as the median SOS of the *Kiremt* growing *season* at Srinka and Kombolcha, respectively, for the period 1978-2008. In another study, Araya and Stroosnijider (2011) and Hadgu *et al*. (2013) noticed comparable findings of the SOS of *Kiremt* growing season being between 1st week of July and 3rd week of July in northern Ethiopia. According to the classification of Hare (1983), the observed variability of *Kiremt* SOS was less (CV = 4 to 6%) and this shows that the past SOS of *Kiremt* growing season have been experienced dependable patterns across the study area. Dependable pattern of sowing date is important for decision making regarding tillage, sowing and other agricultural activities.

Moreover, the observed median end date of *Kiremt* growing season (EOS) was seen being at DOY282 (Oct-8), DOY265 (Sep-21), DOY273 (Sep-29) and DOY279 (Oct-5) at Kombolcha, Kobo, Lalibela and Srinka, respectively. The main rain season (*Kiremt*) terminated earlier than 01 October (DOY275), 12 September (DOY256), 25 September (DOY 269) and 30 September (DOY274) once in four years period at Kombolcha, Kobo, Lalibela and Srinka. The observed low CV values (2-5%) of cessation of *Kiremt* rainfall in the present study indicates that the ending dates for *Kiremt* rainfall vary over a short time span and the patterns could be more understood, and decisions pertaining harvesting and storage could be made easily. Moreover, low CV values of the SOS and EOS of *Kiremt* growing season shows that the variability of crop production in the study region is not necessarily because of the variability of the start and end date of *Kiremt* growing season. As it can be seen from the observed high probability of dry spell occurrence over the North Eastern Amhara, dry spell, late onset and early end date are responsible for crop production in the study area during 1992-2012.

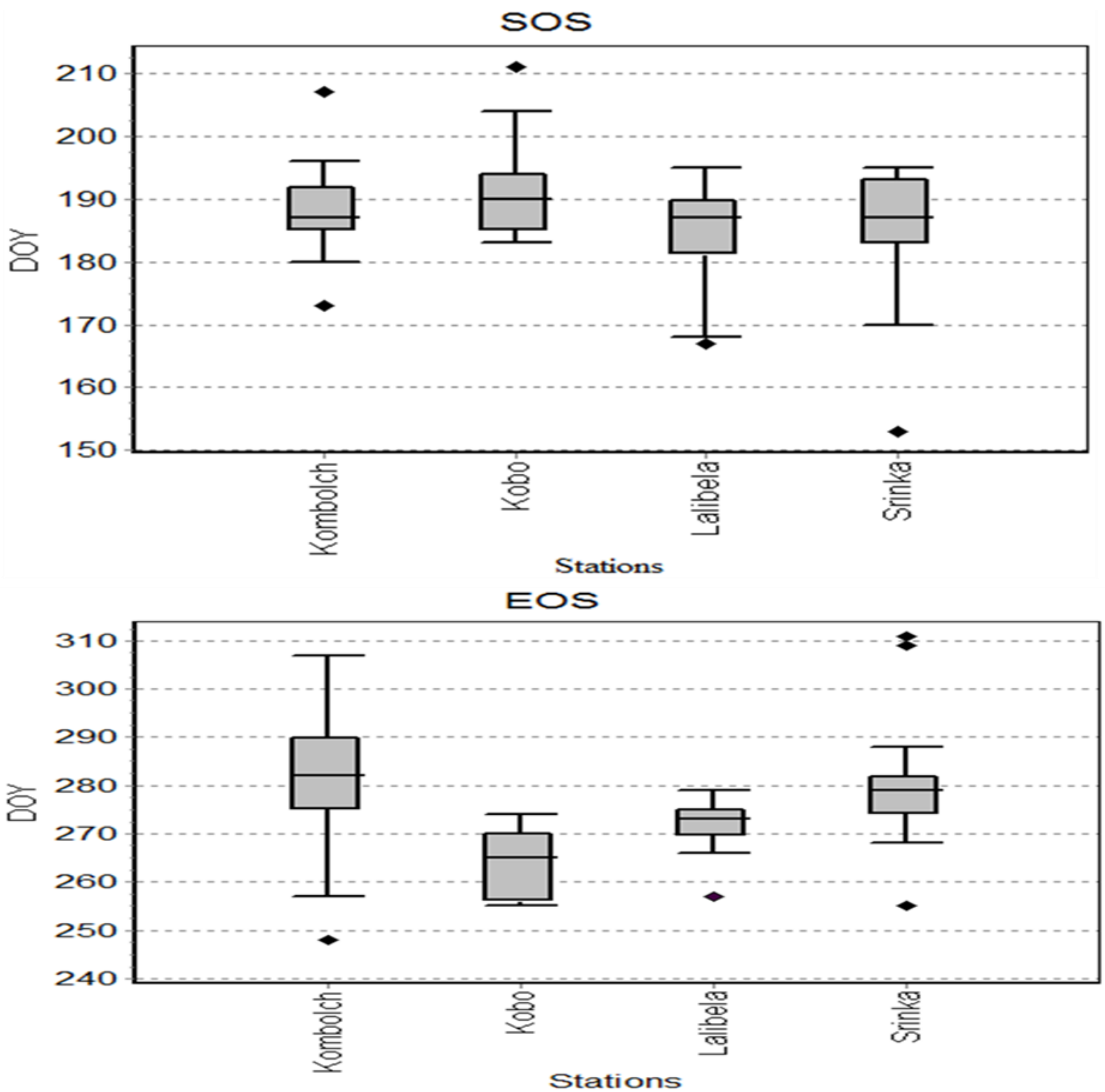

Figure 4. Box and whisker plots for observed start date and end date of *Kiremt* growing season at four stations in the north eastern Amhara, Ethiopia, during 1992-2012.

In the present study, it is possible plant cultivar of 87 days, 64 days, 79 days and 84 days once in four years time at Kombolcha, Kobo, Lalibela and Srinka in the North Eastern Amhara. However, *Kiremt* LGS varied from the shortest 62 days at Kombolcha to the longest 129 days at Srinka during 1992-2012 (Figure 5 and Appendix Table 1). On the other hand, the observed mean LGS of *Kiremt* were 93 days, 74 days, 86 days and 95 days at Kombolcha, Kobo, Lalibela and Srinka, respectively (Appendix Table 1). In line with the present result, Ayalew *et al*. (2012) also reported a comparable median length of 100 and 85 days at Kombolch and Srinka station, respectively for the period 1978-2008. In the present study, the observed CV values also revealed that among the studied stations, *Kiremt* growing season was relatively more variable at Srinka and conversely less variable at Lalibela.

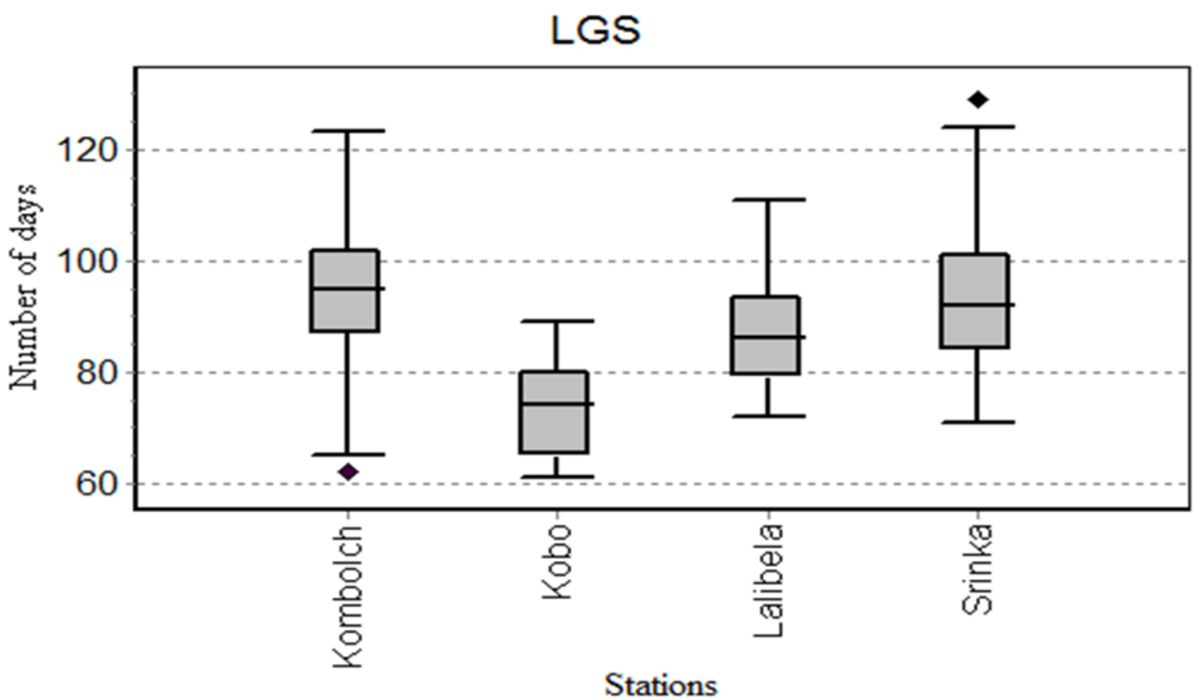

Figure 5. Box and whisker plots for observed length of *Kiremt* growing season at four stations in North Eastern Amhara, Ethiopia, during 1992-2012.

4.1.5.2.Length of *Belg* growing season

The start date (SOS) of rainfall during the *Belg* growing season in the North Eastern Amhara during 1992-2012 is depicted in Figure 6 and Appendix Table 2. In the present study, the start date of *Belg* growing season varied from (March-2) at Srinka to DOY90 (March-30) at Kombolcha and Kobo. A wider range of 27 days between the earliest and the latest start dates were observed at Srinka while narrow range of 18 days was recorded at Lalibela. The mean SOS of *Belg* growing season were observed being DOY84 (Mar-24), DOY81 (Mar-21), 81(Mar-21) and DOY79 (Mar-19) with median start date of DOY70 (Mar-10), DOY70 (Mar-10), DOY71 (Mar-11) and 62 (Mar-2) at Kombolcha, Kobo, Lalibela and Srinka stations respectively. Moreover, on average the *Belg* growing season during the study period started relatively early (by 8 days) at Srinka when compared to that of Kombolcha. The less variability range (CV = 7% to 10%) observed in the present study shows more dependable patterns of the SOS of *Belg* growing season which is more important for decision making regarding tillage, sowing and other agricultural activities. During 1992-2012, the *Belg* growing season experienced high risk of failure of start date of growing season (33-66%) across the study (Appendix Table 2). This shows that there was high risk of planting failure for *Belg* season crops in the study area during 1992-2012.

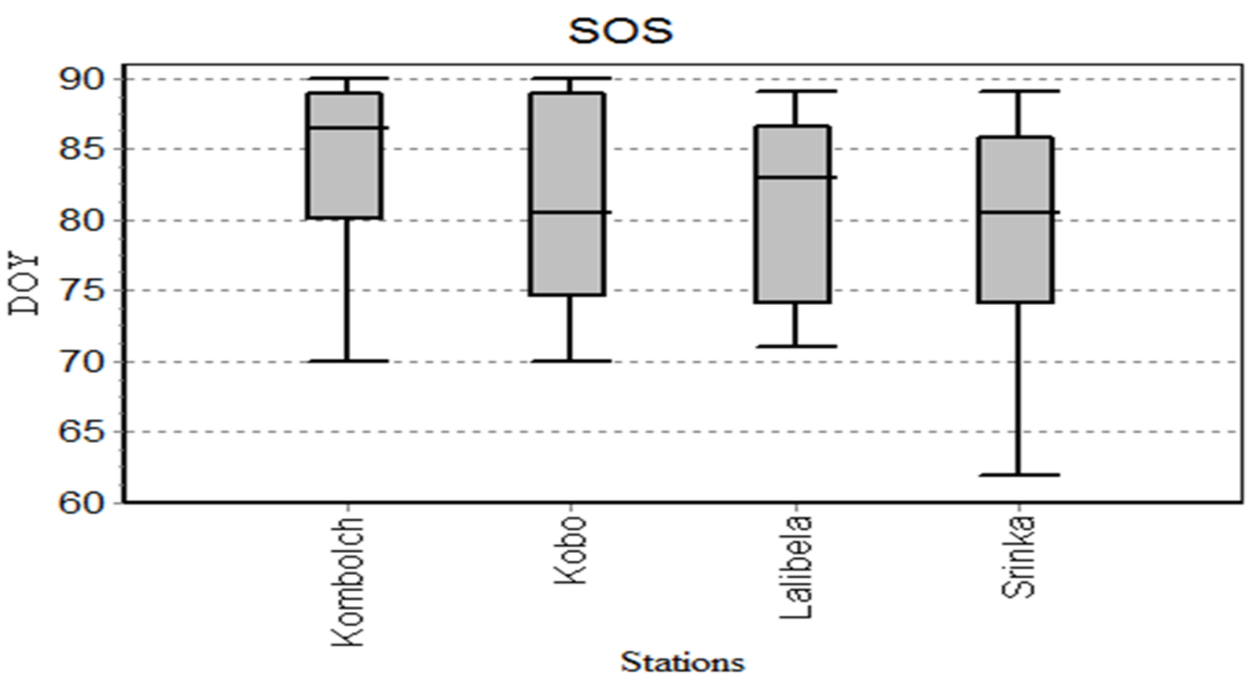

Figure 6. Box and whisker plots for observed start date of *Belg* growing season at four stations in North Eastern Amhara, Ethiopia, during 1992-2012.

On the other hand, the end date of *Belg* growing season (EOS) was observed to be DOY 152 (May-31) and did not show variation between the earliest and the latest EOS during 1992-2012 over the study area (Appendix Table 2). At Srinka, however, the difference between the earliest and the latest EOS was only 4 days, and it shows tendency of extending to the beginning of the *Kiremt* growing season. This indicates connectivity of the *Belg* season with that of the *Kiremt* season.

Unlike the Srinka situation, the late onset of *Kiremt*, towards the end of June or beginning of July at Kombolcha, Lalibela and Kobo is marked by discontinuity between the *Belg* and the *Kiremt* season. This indicates better probability of sowing long maturing crops (sorghum, millet, maize) in *Belg* at Srinka to take advantages of the *Kiremt* season. At the remaining stations however, the observed discontinuity might hamper success of long maturing crops.

Whereas, the length of *Belg* growing season (LGS) varied from the smallest 62 days at Kombolcha and Kobo to the longest 90 days at Srinka (Figure 7 and Appendix Table 2). For the study period, however, the mean value was shortest at Kombolcha (70 days), and longer than this by 5 days at Srinka. The median length of *Belg* growing season ranged from 69 days at both Kombolcha and Lalibela to 73 days at Srinka during 1992-2012. The observed CV values also revealed that among the studied stations, the *Belg* growing season was relatively more variable at Kobo (CV=12%) and conversely less variable (CV=9%) at Srinka. According to the classification of Hare (1983), the observed CV values were less variable. The observed values of *Belg* LGS revealed that successful crop harvest on average requires choice of crop and crop varieties that complete life cycle within not more than 70 days across the study area. As discussed under section 4, the recurrent failure of planting date during past *Belg* growing season indicates rain fed crop production in the study area was at risk.

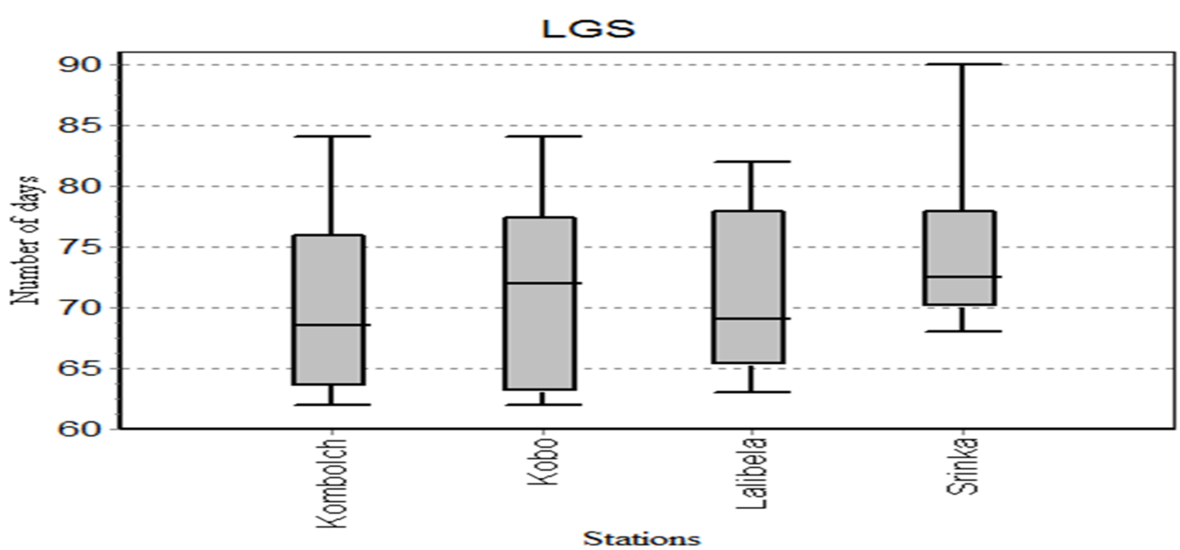

Figure 7. Box and whisker plots for observed length of *Belg* growing season at four stations in North Eastern Amhara, Ethiopia, during 1992-2012.

4.1.6. Length of dry spell

4.1.6.1.Probability of Maximum dry spells length on Calendar basis

Probability of dry spells exceeding 5,7,10 and 15 days length at four stations in the North Eastern Amhara during 1992-2012 is depicted in Figure 8. As indicated in the Figure, the probability of of dry spells occurrence for *Belg* season differs among stations. The probability of dry spell occurrence at 5 days length was above 70% at Kobo and above 90% at Kombolcha, Lalibela and Srinka stations during the Peak rainfall months of *Belg* season DOY 70 (the end of 1st week of March) to DOY120 (the end of 3rd week of April). On the other hand, the observed probability of dry spell occurrence greater than 7days length was 40% at Kobo, 60% at Srinka, 80% at Lalibela and 70% at Kombolcha. Whereas, the probability of dry spell occurrence greater than 10 days length were observed being 10% at Kombolcha, 10% at Kobo, 40% at Lalibela and 30% at Srinka (Figure 8).

The probability of dry spells occurrence longer than 15 days was less than 10% across the study area during the study period. This showed that the probability of dry spells occurrence increases from the 3rd week of April (DOY110) and descends down to 0 (its minimum position) from the middle to end of June over all studied stations, and the period after this is the time when there is minimum risk to the emergence, establishment and subsequent growth of annual crops. The graphs in Figure 8 also demonstrate how the probability of 5 and 7 days of dry spell curves stays at their maximum value of 1.0 (100%) during the earlier and later months relative to the growing seasons. When we looked in to the probability of dry spell occurrence of 5 days length, it was at 0% over the majority locations studied , whereas, over Kobo it was 5% during 1992-2012 main rain season *(Kiremt*) peak months. On the other hand, the probability of dry spells occurrence greater than 7 days length was observed being 0% at all the studied locations (Figure 8).

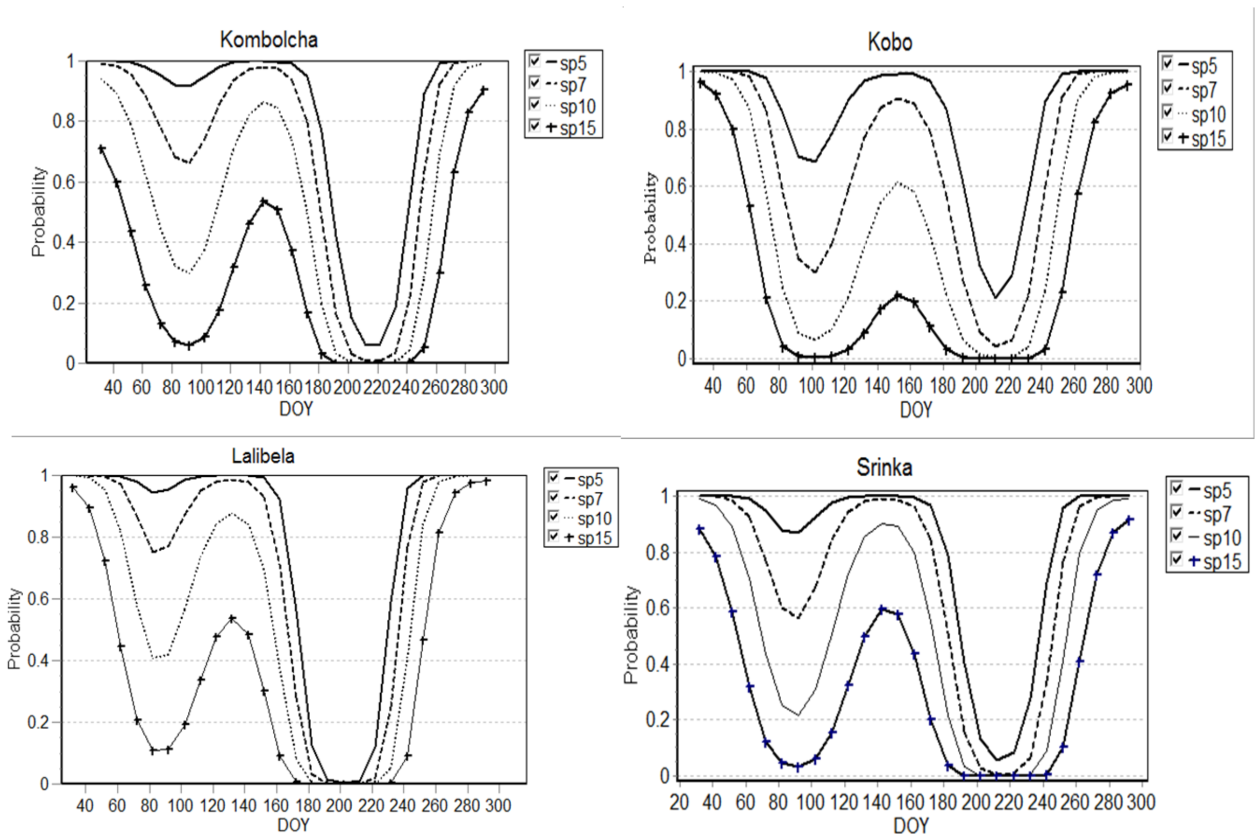

Figure 8. Probabilities of maximum dry spells exceeding 5, 7, 10 and 15 days length within 30 days after starting date at four stations in the North Eastern Amhara, Ethiopia during 1991-2012

From the dry spell graphs one can see that there was no chance for the occurrence of dry spell at greater than 7, 10 and 15 days lengths during the peak months of main (*Kiremt*) rain season. This implies that the predictability of dry spells occurrence at greater than 7 days length were easy for decision makers. As the length of dry spell threshold becomes short, the probability of dry spells occurrence increases and conversely, as the dry spells threshold becomes longer, the probability of dry spells occurrence decreases with-in the growing seasons.

Generally, at all the studied locations, curves of dry spells probability at different lengths converge to their minimum during months of peak rainfall periods and turn upward again from the 1st week of September, signaling end of the growing season. This suggests that standing crops after this time will face increasingly greater risk of water shortage in the study area.

4.1.6.2. Probability of dry spells length on crop calendar basis

Because of the changing nature of planting dates with the variable characteristics of rainfall distribution of each season, calculations of dry spells on a calendar day basis have limited importance for specific application in crop production (Siva Kumar, 1992; Tesfaye and Walker, 2004). Therefore, it is necessary to compute the probabilities of dry spells occurrence after the start dates (successful planting dates) are determined. The computed probabilities of dry spells at different length after successful start date of growing season is established for each location are depicted in Figure 9. The probability of dry spells occurrence longer than 5 days length increased rapidly after 30 days of successful planting date is established at Kombolcha and Srinka and, 20 days after planting at Lalibela and Kobo. In the same manner, the probability of dry spells occurrence longer than 7 days length was observed being increased rapidly 40 days after effective planting date is established at Kombolcha and Srinka whereas, 30 days after planting at Lalibela and Kobo stations.

With regarding to the probability of dry spells occurrence longer than 10 days length , increased rapidly after 50 days of successful planting date is established, (DOY235, August-22) at Kombolcha and Srinka and after 40 days of planting date is established , (DOY227, August-14) at Lalibela and Kobo. On the other hand, the probability of dry spells occurrence longer than 15 days length were increased rapidly after 60 days of successful sowing date is established, (DOY247, September-3) at Kombolcha and Srinka and, increased after 50 days of sowing, (DOY237, August -24) at Kobo and Lalibela stations during 1992-2012.

From the SOS, LGS and dry spell analysis result in the present study for *Kiremt* growing season, it is necessary to choose a terminal drought tolerant variety if one wants to plant a crop variety with a maturity length of more than 74, 86 days, 92 days and 95 days at Kombolcha, Kobo, Lalibela and Srinka, respectively, in order to fully utilize the regions' resources. Choice of a crop or crop variety can be made based on the length of dry spells after successful planting date is established to (Belachew 2002).

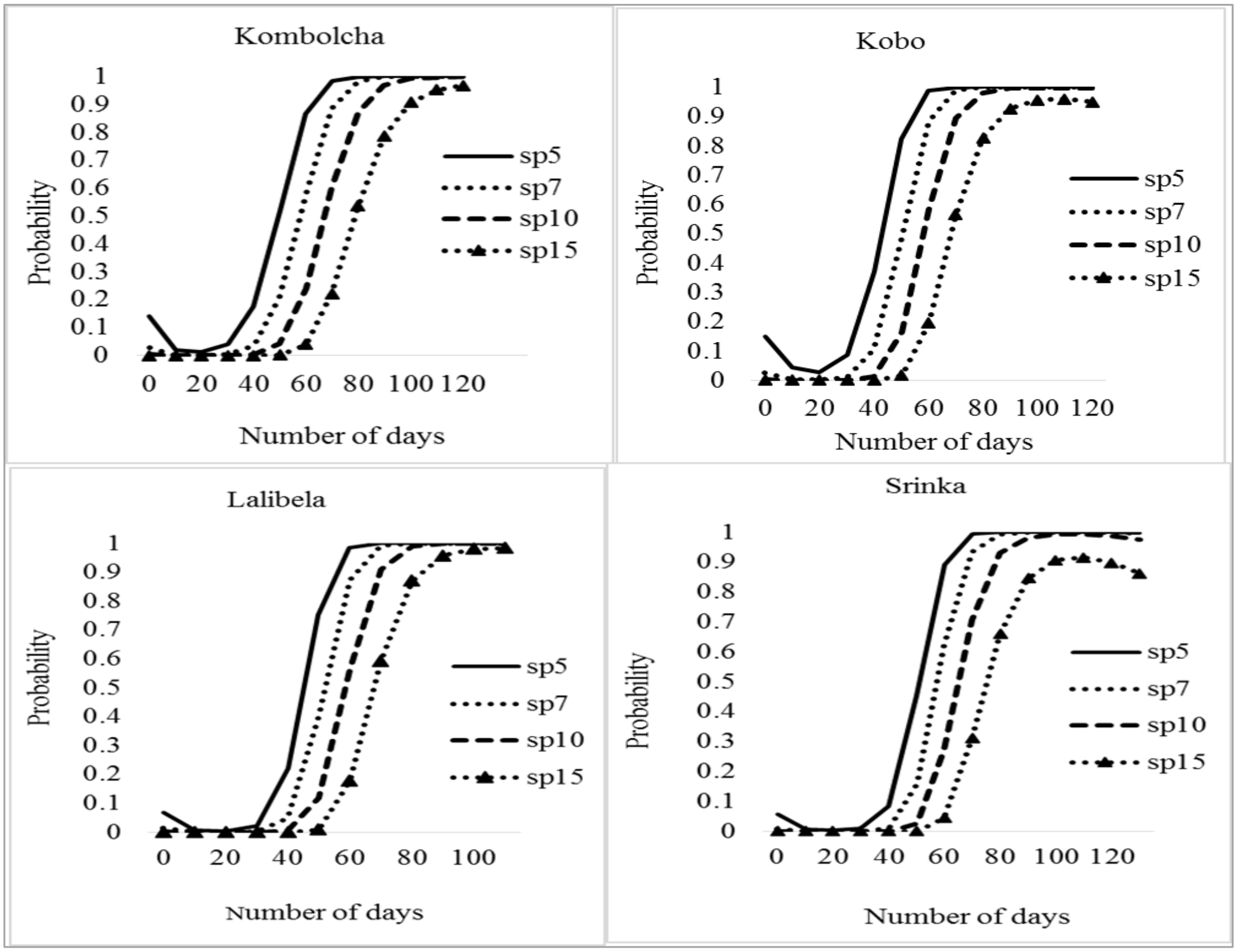

Figure 9. Probabilities of dry spells length exceeding 5, 7, 10 and 15 days on crop calendar basis after successful planting date is established at four stations in the North Eastern Amhara, Ethiopia, during 1992-2012

4.1.7. Observed trends in rainfall characteristics

4.1.7.1.Trends in annual and seasonal rainfall total

Observed trends in annual, seasonal *Kiremt* and *Belg* rainfall totals were presented in Table 6. As shown in the Table 6, during 1992-2012, trends in annual rainfall totals were observed being positive at Kombolcha and Srinka, and conversely negative at Kobo and Lalibela stations. The maximum observed positive rate of change in annual rainfall over the study area was 63.8 mm/decade at Kombolcha and Srinka stations. On the other hand, increasing trend in rainfall of historical *Kiremt* season was observed over the majority of the stations studied during the study period. Moreover, the *Belg* rainfall has shown a declining trend across the study area during the period 1992-2012. On average there was 8.2 mm/decade to 56.3mm/decade decline in the observed seasonal *Belg* rainfall at Kobo and Srinka stations, respectively (Table 6). The observed trends in annual, seasonal *Kiremt* and *Belg* rainfall totals across all seasons however, did not show significant changes at all the stations. In line with this Ayalew *et al*. (2012) also reported declining trends in annual, seasonal *Kiremt* and *Belg* rainfall at Kombolcha and Srinka stations during 1979-2008 period. Similarly Seleshi and Zanke (2004), NMSA (2001). NMA (2007), Cheung *et al*. (2008), McSweeney *et al*. (2008), and Viste *et al*. (2012) also reported statistically non-significant declining tendency in annual rainfall across Ethiopia between of 1960-2006.

Table 6. Observed Trends of annual, seasonal *Kiremt* and *Belg* rainfall totals at four stations in the North Eastern Amhara, Ethiopia, during 1992-2012.

seasons	Observation period	Stations							
		Kombolcha		Kobo		Lalibela		Srinka	
		Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q
Annual	1992-2012	1.49	6.38	-1.54	-5.37	-1.21	-2.26	1.48	6.38
Kiremt	1992-2012	0.05	0.23	-0.75	-2.62	0.09	0.66	0.03	0.20
Belg	1992-2012	-1.10	-4.59	-0.42	-0.82	-1.06	-1.49	-1.18	-5.63

NB: ZMK and Q are Mann Kendal and Sen's slope trend test

4.1.7.2.Trends in seasonal rainy and dry days

During the study period (1992-2012), decreasing trends in number of rainy days (NRD) for the *Kiremt* season were observed at Srinka and Kobo, and conversely increasing trends were observed at Kombolcha and Lalibela stations indicating lack of consistent trend in the NRD in the study area (Table 7). Moreover, to assert changes in the NRD over the study area, the observed trends were not statistically significant at all studied stations. On the other hand, number of dry days (NDD) showed a tendency of increasing trends at Srinka and Kobo, and conversely non-significant decreasing trends at Kombolcha and Lalibela stations indicating lack of consistent trend in NDD for the *Kiremt* growing season in the study area. In line with this, Zanke and Seleshi (2004) reported comparable result that NRD and NDD showed decreasing and increasing change, respectively, over Ethiopia. An increasing change in NDD indicates that rain fed crop production in the study area was at risk of soil moisture stress which resulted in crop failure (Zanke and Seleshi, 2004).

Table 7. Observed trends in seasonal *Kiremt* and *Belg* number of rainy days (NRD) and dry days (NDD) at four stations in the North Eastern Amhara, Ethiopia, during 1992-2012.

Season	Indices	Kombolcha		Kobo		Lalibela		Srinka	
		Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q
Kiremt	NRD	0.95	0.08	-1.79	-0.533	1.36	0.34	-1.15	-0.32
	NDD	-1.09	-0.11	1.73	0.53	-1.24	-0.38	1.15	0.32
Belg	NRD	-1.93	-0.27	-1.21	-0.50	-1.70	-0.44	0.33	0.09
	NDD	1.96*	0.28	1.21	0.50	1.45	0.48	-0.36	-0.09

NB: NRD is Number of rainy days, NDD is number of dry days and Z_{MK} and Q are Mann Kendall and Sen's slope trend test and * indicates significance at 0.05

As depicted in Table 7, on the other hand, seasonal *Belg* NRD have also shown tendency of non-significant declining trends at Kombolcha, Kobo and Lalibela, and conversely increasing trend at Srinka during 1992-2012. Contrarily, the analysis result of the trend in NDD indicated that a tendency of decreasing trend were observed at Kombolcha, Kobo and Lalibela stations. Moreover, the observed increasing change in the NDD of the *Belg* growing season was significant at 0.05 significance level only at kombolcha (2.8 days per decade). Similar to the present study result, Hadgu *et al*. (2013) found variable and non-significant trends in NRD and NDD among four studied stations in the nearby areas of northern Ethiopia.

4.1.7.3.Trends in length of *Kiremt* and *Belg* growing seasons

During the study period (1992-2012), increasing trends in start date (SOS) of the *Kiremt* growing season were observed at three of the four studied stations (Kombolcha, Kobo and Srinka), and conversely, negative trend was observed only at Lalibela (Table 8). Though, the observed trends were not statistically significant at all the studied stations, the positive signs are indications of a tendency of late SOS of *Kiremt* growing season for the last 21 years at most of the stations. Hadgu *et al.* (2013) found significant forward shifting in the start date (indicates Late entrance) of the *Kiremt* growing season at three of four stations studied stations in the adjoining Tigray Region. On the other hand, in the present study an increasing trends in end date (EOS) of the *Kiremt* growing season were observed at Lalibela and Kobo, conversely declining trend in EOS is observed at Kombolcha whereas, no trend is found at Srinka during the study period. However, the observed declining trend in EOS of *Kiremt* growing season was significant only at Kombolcha which implies considerable early EOS of *Kiremt* growing season was observed by 14 days per decade. This significant declining trend in EOS of *Kiremt* season at Kombolcha shows that the location need great attention in case of harvesting time. In line with this, Hadgu *et al*. (2013) again reported significantly increased early cessation of *Kiremt* season rainfall at Mekele and Adigudum stations in the northern Ethiopia.

With regard to the length of *Kiremt* growing seasons (LGS), non-significant declining trends were observed at all the studied stations in the study area, indicating tendency of shorten LGS during the study period, and this corroborates earlier reports of Hadgu *et al*. (2013) who noticed significant reduction trend in the LGS at Alamata, Adigudum, Mekelle and Adigrat stations in the nearby stations to the North Eastern Amhara. The observed declining trends in *Kiremt* LGS, in the present study, over all studied stations indicate that rain fed crop production have been challenged during 1992-2012.

Table 8. Trends in observed start date, end date and length of *Kiremt* and *Belg* growing seasons at four stations in the North Eastern Amhara, Ethiopia, during 1992-2012.

Season	parameters	Stations							
		Kombolcha		Kobo		Lalibela		Srinka	
		Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q
Kiremt	SOS	0.61	0.11	0.61	0.10	-0.07	-0.10	0.49	0.12
	EOS	-2.42*	-1.42	0.62	0.06	0.13	0.33	0.00	0.00
	LGS	-1.87	-0.81	-0.54	-0.13	-0.30	-0.79	-1.10	-0.60
Belg	SOS	1.64	2.50	0.55	0.50	-2.00*	-0.10	0.88	0.50
	EOS	-1.31	-0.50	0.00	0.00	-1.01	-0.17	-0.53	-0.50
	LGS	-1.95	-2.22	-0.42	-0.50	1.01	0.17	-1.10	-0.82

NB: Z_{MK} is Man Kendall trend test, Q is slope of the trend, ***** Significant at 0.05 significance level, SOS is start date, EOS end date and LGS is length of growing season

In the case start date (SOS) of *Belg* growing season, non-significant increasing trends were observed at Kombolcha, Srinka and Kobo that indicate the studied stations were characterized by late start of the *Belg* growing season during 1992-2102. On the other hand, significant declining trend in SOS was observed only at Lalibela (Table 8), indicating a tendency of early SOS of *Belg* growing season was seen for the last 21 years. The observed late SOS had a negative impact on rain fed crop production in the study area, by shortening length of the growing season. The trend analysis revealed that the EOS of the *Belg* growing season have been experienced non-significant decreasing trends at Kombolcha, Srinka and Lalibela and no trends is observed at Kobo. The observed increasing change in the SOS and declining change in EOS of the historical *Belg* growing season resulted in a concomitant change in *Belg* length of growing season (LGS) over the study area. As shown in Table 8, the LGS of *Belg* growing season has shown decreasing trend at kombolcha, Kobo and Srinka, and conversely a tendency of increasing change is observed at Lalibela. Generally, increasing trend in SOS at both seasons indicates late entrance of the growing season and/or declining trend in EOS shows early entrance of the growing seasons during the study period. The combination of late start and early end date of growing season resulted in shorten LGS which affected greatly crop types/cultivars to be grown in the study area for the past 21 years.

4.2. Future (2021-2040) Rainfall Variability and its Trends

Even though the projected mean change of future intra seasonal rainfall variables with the observed intra seasonal rainfall variables at all the studied stations is well analyzed and discussed under sub section 4.2.6, summary statistics of future intra seasonal rainfall variables are presented and discussed here.

4.2.1. Annual rainfall totals

The projected summary statistics of annual rainfall by 2030s under RCP4.5 emission scenario using three GCMs (CSIRO Mk 3.6.0, Had GEM2-ES and MIROC ESM CHEM) at Kombolcha, Kobo, Lalibela and Srinka stations is depicted in Table 9. According to the prediction of the CSIRO, Had and MIROC, the future annual rainfall totals will vary depending on the GCMs and stations used in the study. For instance, the prediction of CSIRO revealed that the future annual rainfall totals will vary from the minimum of 593.7 mm at Kobo to the maximum of 1079.0 mm at Srinka with projected mean rainfall of 658.6 mm and 1017.4 mm, respectively. The Had model, on the other hand, predicted from the minimum of 635.8 mm at Kobo to the maximum of 1143.4 mm at Srinka with the respective mean rainfall of 657.7 mm and 1061.1 mm. Whereas, the MIROC model predicted annual rainfall totals to be ranged from the minimum of 742.3 mm at Kobo to the maximum of 1153.0 mm at Kombolcha with projected mean rainfall of 681.5 mm and 1095.2 mm, respectively (Table 9).

The projected coefficient of variability of future annual rainfall totals in Table 9 also revealed that the CV value predicted by the three GCMs over the selected stations will be low. Whereas, the SD of the future annual rainfall totals will be expected to vary from the minimum of 32.6mm at Kobo to the maximum of 50.9mm at Kombolcha as predicted by the CSIRO, from the minimum of 9.4 mm at Kobo to the maximum of 62.7mm at Srinka as predicted by the Had, and from the minimum of 21.6 mm at Lalibela to the maximum of 59.8 mm at Srinka as predicted by MIROC in the North Eastern Amhara. Hence, al-most at all the studied stations, moderate to low stability of future annual rainfall totals will be expected as classified by Reddy (1990). Various researchers reported comparable result that in the future moderate to high SD values for annual rainfall totals will be expected in the northern Ethiopia (Kassie *et al.,* 2014; Hadgu *et al*., 2014). According to Reddy (1990), this moderate to high SD values indicates that the future annual rainfall will be less stable. The projected less stability makes the rainfall less predictable and unreliable for rain fed crop production in the study area

Table 9. Summary statistics of annual rainfall totals by 2021-2040 under RCP4.5 emission scenario CSIRO, Had and MIROC models at four stations in the North Eastern Amhara, Ethiopia

Statistics	Years		
	2030s_RCP4.5_CSIRO	2030s_RCP4.5_Had	2030s_RCP4.5_MIROC
	Kombolcha		
Max (mm)	1038.3	1026.5	1153.0
Mean (mm)	963.7	973	1095.2
Min (mm)	909.1	913.5	1002.5
CV %	5.3	4	3.7
SD (mm)	50.9	39.1	40.2
	Kobo		
Max (mm)	696.3	662.1	742.3
Mean (mm)	658.6	657.7	681.5
Min (mm)	593.7	635.8	608.5
CV %	5	1.4	6.7
SD (mm)	32.6	9.4	45.9
	Lalibela		
Max (mm)	1000.2	959.5	1063.6
Mean (mm)	944.2	875.7	1028.8
Min (mm)	857.3	794.7	989.2
CV (%)	4	4.8	2.1
SD (mm)	37.8	41.9	21.6
	Srinka		
Max (mm)	1079	1143.4	1082.6
Mean (mm)	1017.4	1061.1	1018.5
Min (mm)	925	955.0	932.8
CV (%)	4.2	5.9	5.9
SD (mm)	42.5	62.7	59.8

NB: CV is Coefficient of Variation and SD is Standard Deviation

4.2.2. Seasonal rainfall totals

As depicted in Table 10, the future *Kiremt* rainfall will vary by 2030s among models and studied stations. Accordingly, the CSIRO model predicted to vary from the minimum of 365.9 mm at Kobo to the maximum of 752.4 mm at Lalibela with the projected mean of 379.4 mm and 719.5 mm, respectively. On the other hand, the Had model predicted variations from the minimum of 346.7

mm at Kobo to the maximum of 689.8 mm at Kombolcha with the projected mean of 347.9 mm and 685.9 mm, respectively. Similarly, the prediction by MIROC model indicated that the future *Kiremt* rainfall totals will vary from the minimum of 289.4 mm at Kobo to the maximum of 750.9 mm at Kombolcha with the respective projected mean of 343.6 mm and 711.2 mm. The projected coefficient of variability (CV) for future *Kiremt* rainfall totals revealed CV from 3% at Srinka to 4 % at Kombolcha as predicted by CSIRO. It will vary from 0.2% at Kobo to 3% at Srinka as predicted by the Had, and from 2% at Srinka to 11% at Kobo by MIROC. The seasonal contribution of *Kiremt* rainfall to the annual totals will vary from 58% at Kobo to 76% at Lalibela as predicted by CSIRO; from 53% at Kobo to 71% at Kombolcha as predicted by Had, and from 50.4% at Kobo to 67% at Lalibela as predicted by MIROC model. The future projected SD of 36.6mm by MIROC also shows that the future *Kiremt* season rainfall at Kobo is expected to be less stable (Reddy, 1990).

With regard to the future seasonal *Belg* rainfall totals, the three GCMs varied in prediction for the study period (2021-2040). For instance, the CSIRO model predicted variation from the minimum of 109. 6 mm to the maximum of 226.7 mm at Lalibela, with the projected mean of 171.1 mm. Similarly, the Had model also predicted from the minimum of 160.9 mm to maximum of 344.3 mm again at Lalibela with predicted mean of 244.7 mm. On the other hand, the MIROC model projected the future *Belg* rainfall from minimum of 186.9 mm at Kombolcha to maximum of 308.4 mm at Srinka with respective mean of 197.1 mm and 260.9 mm. The projected seasonal contribution of *Belg* rainfall to the annual totals will also vary from 18% % at Lalibela and Srinka to 27% at Kobo as predicted by CSIRO. It will vary from 9% at Srinka to 34% at Kobo as predicted by the Had, and from 20% at Srinka to 34% at Kobo as predicted by MIROC. From this, it can be observed that annual rainfall totals at Kobo station will receive more *Belg* rainfall contribution than that of the rest stations studied for the years 2021-2040.

Table 10. Summary statistics for *Kiremt* and *Belg* rainfall totals by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC GCMs at four stations in the North Eastern Amhara, Ethiopia.

Stations	Statistics	Years_2030s_RCP4.5					
		CSIRO		Had		MIROC	
		Kiremt	*Belg*	*Kiremt*	*Belg*	*Kiremt*	*Belg*
Kombolcha	Max (mm)	749.3	209.6	689.8	259	750.9	215.4
	Mean (mm)	703.3	193.1	685.9	224.1	711.2	197.1
	Min (mm)	676.5	178.2	677.4	192.9	665.4	186.9
	CV (%)	4	5	1	10	3	5
	SD (mm)	30.9	9.5	3.5	22	24.5	9.4
	CT (%)	73	20	71	23	65	20
Kobo	Max (mm)	399.4	202.1	348.6	229.1	390	271.4
	Mean (mm)	379.4	180.2	347.9	225	343.6	231.9
	Min (mm)	365.9	166.3	346.7	203.1	289.4	205.2
	CV (%)	4	8.9	0.2	4.2	11	12
	SD (mm)	13.9	15.9	0.6	9.4	36.7	26.3
	CT (%)	58	27	53	34	50.4	34
Lalibela	Max (mm)	752.4	226.7	633.4	344.3	712.7	292.8
	Mean (mm)	719.5	171.1	614.2	244.7	689.2	245
	Min (mm)	701.2	109.6	579	160.9	646.2	202.9
	CV (%)	6	18	2	19	3	12
	SD (mm)	12.7	30.9	13.7	46.8	21.5	28
	CT (%)	76	18	70	28	67	23.8
Srinka	Max (mm)	729.4	211.4	749.4	305.9	645.7	308.4
	Mean (mm)	696.1	192.9	699.3	261.7	621.8	260.9
	Min (mm)	657.6	165.2	678.1	224.0	596.7	202.1
	CV (%)	3	8	3	13	3	18
	SD (mm)	21.7	15.8	21.9	32.8	15	46
	CT (%)	69	18	66	9	61	26

NB: CV is coefficient of variation, SD is standard deviation and CT is totals contribution

When we looked in to the projected coefficient of variability (CV) for future *Belg* rainfall totals, rainfall will vary from 5 % at Kombolcha to 18% at Lalibela as predicted by the CSIRO; from 4% at Kobo to 19% at Lalibela as predicted by the Had , and from 5% at Kombolcha to 18% at Srinka as predicted by the MIROC model. The relatively high CV values predicted at Lalibela and Srinka stations indicate that the future *Belg* rainfall will be less predictable. Furthermore, according to Reddy (1990), the projected SD values predicted by Had and MIROC (31 and 47) shows that the future *Belg* rainfall totals will be expected to be less stable at Lalibela station.

4.2.3. Length of growing seasons variability

4.2.3.1. Length of *Kiremt* growing season

The projected start date (SOS) of future *Kiremt* growing season by 2030s under RCP4.5 emission scenario using CSIRO, Had and MIROC models at the four stations in North Eastern Amhara is presented and discussed in Table 11 (a and b). As shown in the table 11, models differed in prediction of the future SOS of *Kiremt* growing season. For instance, the projected SOS of future *Kiremt* growing season by CSIRO model will vary from the earliest DOY 178 (Jun-26) at Lalibela to the latest DOY190 (Jul-8) at Kobo and Srinka stations. The Had model also predicted the SOS of *Kiremt* to vary from earliest of DOY 176 (June-24) to the latest of DOY 188 (Jul-6) at Lalibela. The MIROC model on the other hand predicted the SOS of *Kiremt* to be from the earliest DOY 176 (June-24) to the latest DOY 190 (July-8) at Lalibela, and kobo and Srinka stations, respectively. The coefficient of variability (CV) for the future SOS of *Kiremt* rainfall, however, revealed less variability by all GCMs under RCP4.5 emission scenario according to the CV classification of Hare (1983). The projected less CV value indicates more dependable patterns of SOS of future *Kiremt* growing season which is more important for decision making regarding tillage, sowing and other agricultural activities in the study area.

On the other hand, the probable end date (EOS) of future *Kiremt* growing season predicted by CISRO varied from the earliest DOY241 (August-28) at Srinka to the latest DOY 266 (September-22) at Lalibela. The Had also predicted the end date of future *Kiremt* season from the earliest DOY 228 (August -15) at kobo to the latest DOY260 (September -16) at Lalibela. The MIROC model predicted the EOS of future *Kiremt* season from the earliest DOY237 (August-23) at kobo to the latest DOY262 (September-18) at Lalibela. The projected CV for the future *Kiremt* rainfall EOS revealed less variability by all GCMs at all studied stations (Table 11). This implies that by 2030s the projected EOS of future *Kiremt* growing season will vary over a short time span and that the patterns of EOS of *Kiremt* growing season will be expected to be more understood, and decisions pertaining to harvesting and storage will probably be made more easily.

Table 11. Summary statistics of projected start and end date of *Kiremt* growing season at (a) Kombolcha and Kobo (b) Lalibela and Srinka for 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models in the North Eastern Amhara, Ethiopia.

(a) Start date and end date for Kombolcha and Kobo

Indices	Year_2030s	Stations				
		Kombolcha				
		Latest (DOY)	Mean (DOY)	Earliest (DOY)	CV (%)	SD (DOY)
SOS	RCP 4.5_CSIRO	178(Jun-26)	178(Jun-26)	178(Jun-26)	0	0
	RCP4.5_Had	185(Jul-3)	185(Jul- 3)	185(Jul-3)	0	0
	RCP4.5_MIROC	189(Jul-7)	188(Jul-6)	181(Jun-29)	2	3
EOS	RCP 4.5_CSIRO	259(Sep-15)	253(Sep-9)	251(Sep-11)	2	4
	RCP4.5_Had	259(Sep-15)	257(Sep-17)	256(Sep-16)	1	1
	RCP4.5_MIROC	260(Sep-16)	259(Sep-15)	258(Sep-18)	0	1
		Kobo				
SOS	RCP 4.5_CSIRO	190(Jul-8)	183(Jul-1)	181(Jun-29)	2	3
	RCP4.5_Had	180(Jun-28)	179(Jun-27)	179(Jun-27)	1	1
	RCP4.5_MIROC	190(Jul-8)	190(Jul-8)	190(Jul-8)	0	0
EOS	RCP 4.5_CSIRO	244(Aug-31)	242(Aug-29)	241(Aug-28)	0	1
	RCP4.5_Had	230(Aug-17)	229(Aug-16)	228(Aug-15)	1	1
	RCP4.5_MIROC	244(Aug-31)	239(Aug-26)	237(Aug-24)	1	3

(b) Start date and end date for Lalibela and Srinka

Indices	Year_2030s	Stations				
		Lalibela				
		Latest (DOY)	Mean (DOY)	Earliest (DOY)	CV (%)	SD
SOS	RCP 4.5_CSIRO	184(Jul-2)	182(Jun-30)	178(Jun-26)	1	3
	RCP4.5_Had	188(Jul-6)	180(Jun-28)	176(Jun-24)	2	4
	RCP4.5_MIROC	186(Jul-4)	182(Jun-30)	176(Jun-24)	2	4
EOS	RCP 4.5_CSIRO	266(Sep-22)	266(Sep-22)	266(Sep-22)	0	0
	RCP4.5_Had	260(Sep-16)	260(Sep-16)	259(Sep-15)	0	0
	RCP4.5_MIROC	262(Sep-18)	261(Sep-17)	261(Sep-17)	0	0
		Srinka				
SOS	RCP 4.5_CSIRO	190(Jul-8)	183(Jul-1)	181(Jun-29)	2	3
	RCP4.5_Had	179(Jun-28)	179(Jun-28)	179(Jun-28)	0	0
	RCP4.5_MIROC	190(Jul-8)	190(Jul-8)	190(Jul-8)	0	0
EOS	RCP 4.5_CSIRO	253(Sep-9)	249(Sep-5)	245(Sep-1)	1	3
	RCP4.5_Had	245(Sep-1)	245 (Sep-1)	245(Sep-1)	0	0
	RCP4.5_MIROC	250(Sep-6)	246(Sep-2)	245(Sep-1)	1	2

NB: SOS is start of season, EOS is end of season, DOY is day of year, CV is coefficient of variation and SD is standard deviation

With regard to the predicted future length of *Kiremt* growing period (LGS), the predictions of CISRO varied from the shortest 52 days at kobo to the longest 88 days a Lalibela. The Had model predicted LGS of *Kiremt* growing season will vary from the shortest 49 days at Kobo to the longest 84 days at Lalibela. On the other hand, the MIROC model predicted LGS for *Kiremt* season to be in the range of 49 days at Kobo to the longest 83 days at Lalibela (Table 12). The projected mean LGS of future *Kiremt* growing season.

The three GCMs (CSIRO, Had and MIROC) predicted less CV values of length of *Kiremt* growing season under RCP4.5 emission scenario by 2030s. The degree of CV classification is based on Hare (1983) classification. The projected less CV indicates that the predicted future length of *Kiremt* growing season will be predict able easily by the local farmers. However predicted mean length of future *Kiremt* growing season will be very short at Kobo projected to be 50 days by Had model to

59 days by CSIRO model which indicates that the projected LGS for future *Kiremt* will not be suitable even for drought resistance rain fed crop for the location by 2030s. In general all the studied stations need attention in case of cultivar selection to be grown in the North Eastern Amhara by 2030s.

Table 12. Summary statistics of projected length of *Kiremt* growing season at four stations by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models in the North Eastern Amhara, Ethiopia.

Indices	Year_2030s	Stations									
		Kombolcha					Kobo				
		Longest (days)	Mean(days	Shortest (days)	CV (%)	SD(days	Longest (days)	Mean (days)	Shortest (days)	CV (%)	SD(days
LGS	RCP 4.5_CSIRO	81	75	73	5	4	62	59	52	6	4
	RCP4.5_Had	74	72	69	2	1	51	50	49	1	1
	RCP4.5_MIROC	79	71	69	5	3	54	51	49	5	3
		Lalibela					Srinka				
LGS	RCP 4.5_CSIRO	88	84	82	3	3	70	69	68	1	1
	RCP4.5_Had	84	80	71	5	4	69	68	67	1	1
	RCP4.5_MIROC	83	79	75	5	4	69	69	68	1	1

NB: LGS is length of growing season, CV is coefficient of variation and SD standard deviation

4.2.3.2.Length of *Belg* growing season variability

The projected start (SOS) and end (EOS) date of future *Belg* growing season by 2030s (2021-2040) at four stations in the North Eastern Amhara Region is presented and discussed in Table 13 a and b. As shown in the Table 13, GCMs (CSIRO, Had and MIROC) varied in prediction of the future SOS of *Belg* growing season. For instance, the SOS of future *Belg* growing season by CSIRO model will vary from the earliest DOY 80 (March-20) at Kobo to the latest DOY141 (May-20) at Lalibela. The Had model, predicted the SOS of *Belg* growing season to be in the range of DOY106 (April-15) to the latest DOY133 (May-12) at Lalibela. On the other hand, the MIROC model predicted the SOS of future *Belg* growing season to be in the range of DOY108 (April-17) at Kobo to the latest DOY123 (May-2) at Srinka . The predicted coefficient of variation (CV) for the future

SOS of *Belg* growing season revealed that less variability will be observed at all the studied stations by all GCMs for 2021-2040 (Table 13). As described in Hare (1983), the classification of CV of present study can be grouped under less category and, this implies that the predicted SOS of future *Belg* growing season will have dependable patterns over the study area and consequently this will be important for decision makers in case of sowing date.

Table 13 . Summary statistics of projected start and end date of Belg growing season at (a) Kombolcha and Kobo and (b) Lalibela and Srinka by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC GCMs in the North Eastern Amhara, Ethiopia.

(a) Kombolcha and Kobo

Indices	Year_2030s	Stations				
		Kombolcha				
		Latest (DOY)	Mean (DOY)	Earliest (DOY)	CV (%)	SD (DOY)
SOS	RCP 4.5_CSIRO	117(April-26)	117(April-26)	117(Apr-26)	0	0
	RCP4.5_Had	117(April-26)	115(April-24)	114(April-23)	1	2
	RCP4.5_MIROC	118(April-27)	117(April-26)	117(April-26)	0	0
EOS	RCP 4.5_CSIRO	152(May-31)	152(May-31)	152(May-31)	0	0
	RCP4.5_Had	157(Jun-5)	153(Jun-1)	152(May-31)	1	2
	RCP4.5_MIROC	155(Jun-3)	153(Jun-1)	152(May-31)	1	1
		Kobo				
SOS	RCP 4.5_CSIRO	108(Apr-17)	98(April-7)	80(Mar-20)	14	14
	RCP4.5_Had	106(Apr-15)	106(Apr-15)	106(Apr-15)	0	0
	RCP4.5_MIROC	111(Apr-20)	109(April-18)	108(Apr-17)	1	2
EOS	RCP 4.5_CSIRO	152(May-31)	152(May-31)	152(May-31)	0	0
	RCP4.5_Had	152(May-31)	152(May-31)	152(May-31)	0	0
	RCP4.5_MIROC	155(Jun-3)	153(Jun-1)	152(May-31)	1	1

(b) Lalibela and Srinka

Indices	Year_2030s	Latest (DOY)	Mean (DOY)	Earliest (DOY)	CV (%)	SD (DOY)
		Lalibela				
SOS	RCP 4.5_CSIRO	141(May-20)	127(April-5)	71(Mar-11)	20	25
	RCP4.5_Had	133(May-12)	124(April-2)	115(Mar-24)	6	8
	RCP4.5_MIROC	122(Mar-31)	120(Mar-29)	120(Mar-29)	0	0
EOS	RCP 4.5_CSIRO	160(Jun-8)	154(Jun-2)	152(May-31)	2	3
	RCP4.5_Had	162(Jun-10)	156(Jun-4)	152(May-31)	2	4
	RCP4.5_MIROC	168(Jun-16)	165(Jun-13)	161(Jun-9)	1	2
		Srinka				
SOS	RCP 4.5_CSIRO	122(May-1)	120(April-29)	119(April-28)	1	1
	RCP4.5_Had	117(April-27)	117(April-27)	116(April-25)	0	0
	RCP4.5_MIROC	123(May-2)	121(April-30)	120(April-29)	1	1
EOS	RCP 4.5_CSIRO	153(Jun-1)	153(Jun-1)	152(May-31)	0	1
	RCP4.5_Had	161(Jun-9)	156(Jun-4)	153(Jun-1)	2	2
	RCP4.5_MIROC	173(Jun-21)	160(Jun-8)	142(May-21)	9	14

NB: SOS is start date of growing season, EOS is end date of growing season, DOY is day of year, CV is coefficient of variation and SD is standard deviation

On the other hand, the probable end date (EOS) of future *Belg* growing season predicted by CISRO model varied from the earliest DOY 152 (May-31) at Kombolcha and Kobo to the latest DOY 168 (June-6) at Lalibela. Whereas, the Had model predicted the end date (EOS) of future *Belg* growing season to be in the range of the earliest DOY 152 (May-31) at Kombolcha, Kobo and Lalibela to the latest DOY 162 (June-10) at Lalibela. The MIROC model, predicted the EOS of future *Belg* growing season to vary from the earliest DOY 142 (May-21) to the latest DOY 173 (June-21) at Srinka. The projected CV for the future predicted EOS of *Belg* growing season also revealed the future *Belg* season will be less variable at all the stations under all the three GCMs (Table 13 a and b). The predicted less CV values imply that the EOS for future *Belg* growing season will be expected to be easily predict able and this helps farmers to take decisions pertaining to harvesting and storage will probably be made more easily.

With regard to the predicted future length of *Belg* growing season (LGS), the projected summary statistics are depicted in Table 14. As described in the table 14, the predictions will vary according to the prediction of GCMs (CSIRO, Had and MIROC) used in the study. For instance, the CISRO model projected from the shortest 11 days at Lalibela to the longest 81 days at Lalibela. This wide range at Lalibela indicates that the location will experience high *Belg* LGS variability and the decision will be difficult in case of crop/verities selection to plant in the location by 2030s. The Had model also predicted future *Belg* LGS from the shortest 20 days at Lalibela to the longest 46 days at both kobo and Lalibela stations. On the other hand, the MIROC model predicted future length of *Belg* growing period from the shortest 22 days to the longest 52 days at Srinka.

Table 14 . Summary statistics of projected length of *Belg* growing season at four stations by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC GCMs in the North Eastern Amhara, Ethiopia.

Indices	Year_2030s	Stations									
		Kombolcha					Kobo				
		Longest (days)	Mean (days	Shortest (days)	CV (%)	SD (days)	Longest (days)	Mean (days)	Shortest(days)	CV (%)	SD(days
LGS	RCP 4.5_CSIRO	35	35	35	0	0	72	54	44	25	14
	RCP4.5_Had	43	38	35	6	2	46	46	46	0	0
	RCP4.5_MIROC	44	43	42	2	1	44	43	42	2	1
		Lalibela					Srinka				
LGS	RCP 4.5_CSIRO	81	28	11	87	24	34	33	30	5	2
	RCP4.5_Had	46	32	20	31	10	44	39	36	6	2
	RCP4.5_MIROC	48	44	39	5	2	51	39	22	33	13

The projected CV values for the future predicted *Belg* LGS revealed less variability by all GCMs at most of the studied station. This indicates that the predicted future *Belg* LGS will be less variable, according to Hare (1983) CV classification. Across the North Eastern Amahra semi-arid areas, the predicted mean length of *Belg* growing season will be too short (28- 54 days). From this, one can understand that rain fed crop production, including drought tolerant crops/varieties, will be at risk by 2030s. In line with this, Kassie *et al*. (2014) reported that in the future no more planting is possible in *Belg* season by 2030 and 2050. From the present study and past reports, the future *Belg* growing season, particularly for the North Eastern Amhara, will not be suit able even for drought resistance crops by 2030s.

4.2.3.3.*Kiremt* season rainy and dry days

The projected number of rainy days (NRD) of the future *Kiremt* season at four stations in the North Eastern Amhara is presented and discussed in Table 15. As shown in the table 15, GCMs (CSIRO, Had and MIROC) differed in prediction of the future NRD for the *Kiremt* season. The NRD of the future *Kiremt* season as predicted by CSIRO will vary from the minimum of 38 days at Srinka to the maximum of 48 days at Lalibela stations. The Had model also predicted the NRD for future *Kiremt* to vary from the minimum of 27 days at Kobo to maximum of 48 at Lalibela. The MIROC on the other hand, predicted the NRD to be ranging from the minimum of 26 days at Kobo to the maximum of 49 days at Lalibela.

According to the classification of Hare (1983), the projected CV of NRD for future *Kiremt* growing season will be expected to be less at all the studied stations as predicted by all GCMs for 2030s (Table 15). The projected less CV values indicates that the future NRD for future *Kiremt* will be dependable for decision makers. As SOS has high relationship with NRD and seasonal rainfall totals (not included in this paper), dependability of NRD will be good for decision making in case of rainfall totals and SOS for specific growing season.

Table 15. Summary statistics of seasonal *Kiremt* number of rainy and number of dry days by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models at four stations in the North Eastern Amhara, Ethiopia.

	NRD									
	Kombolcha					Kobo				
Year_2030s	Max (days	Mean (days	Min (days	CV (%)	SD (days	Max (days	Mean (days	Min (days	CV (%)	SD (days
RCP 4.5_CSIRO	39	39	39	0	0	25	27	25	0	39
RCP4.5_Had	45	45	44	2	1	27	27	27	0	45
RCP4.5_MIROC	35	34	33	7	3	26	28	24	9	35
	Lalibela					Srinka				
RCP 4.5_CSIRO	48	44	40	2	1	32	35	38	1	48
RCP4.5_Had	48	46	45	2	1	37	38	40	4	48
RCP4.5_MIROC	49	47	45	3	1	37	38	40	5	49
	NDD									
Year_2030s	Kombolcha					Kobo				
RCP 4.5_CSIRO	83	83	83	1	1	97	95	92	2	83
RCP4.5_Had	78	77	77	1	1	95	95	95	0	78
RCP4.5_MIROC	87	88	89	3	3	96	94	91	3	87
	Lalibela					Srinka				
RCP 4.5_CSIRO	90	88	77	1	1	90	87	84	2	90
RCP4.5_Had	90	86	77	1	1	85	84	82	2	90
RCP4.5_MIROC	92	85	77	2	2	85	84	82	1	92

NB: NRD is number of rainy days, NDD is number of dry days, CV is coefficient of variation and SD is standard deviation.

Similarly, the predicted number of dry days (NDD) for the future *Kiremt* season also varied among GCMs. Accordingly, the CSIRO model predicted the NDD of the future *Kiremt* season varying from the minimum of 77 days at Lalibela to the maximum of 97 days at Kobo; the Had predicted, from the minimum of 77 days at Kombolcha and Lalibela to maximum of 95 days at Kobo, and the MIROC model predicted from the minimum of 77 days at Lalibela to the maximum of 96 days at Kobo. All GCMs predicted that, Lalibela weather station will have the minimum NDD while Kobo station will have the maximum NDD by 2030s (20211-2040). The projected CV for the NDD in the future *Kiremt* season is projected to be less at all the studied stations.

4.2.3.4.*Belg* season rainy and dry days

The predicted number of rainy days (NRD) for the future *Belg* season at the four stations in the North Eastern Amhara is depicted in Table 16. As it can be noticed from the table 16, the GCMs (CSIRO, Had and MIROC) varied in prediction of NRD for future *Belg* season over the area of study. Accordingly, the CSIRO model projected NRD for the future *Belg* season will be varied from the minimum of 18 days at Lalibela to the maximum of 28 days at Kobo. For the same season the Had model predicted the NRD to be in the range of 18 days at Lalibela to the maximum of 32 days at Kobo. On the other hand, the MIROC model predicted the NRD for the future *Belg* season to be varying from the minimum of 21 days at Lalibela to the maximum of 30 days at Kobo stations. All GCMs agreed in the prediction of the minimum NRD at Lalibela, and the maximum of NRD at Kobo stations for the future seasonal *Belg* (Table16). According to the degree of CV classification by Hare(1983), the projected CV values of the future seasonal *Belg* NRD will be less as predicted by all GCMs at all studied stations for 2030s.

Similar to the projected Kiremt NRD, GCMs differed in prediction of number of dry days (NRD) for the future *Belg* season by 2030s across the study area. For instance, the CSIRO model predicted NRD to vary from the minimum of 92 days at Kobo to the maximum of 100 days at Srinka. The Had model predicted to vary from the minimum of 86 days at Kobo to maximum of 100 days at Lalibela. On the other hand, the MIROC models projected the NRD for the future seasonal *Belg* to vary from the minimum of 89 days at Kobo to the maximum of 99 days at Lalibela and Srinka stations. The projected variability of NRD will be less at all stations for 2021-2040 (Table 16).

Table 16. Summary statistics of seasonal *Belg* number of rainy and number of dry days by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC GCMs at the four stations in the North Eastern Amhara, Ethiopia.

	NRD									
	Kombolcha					Kobo				
Year_2030s	Max (days	Mean (days	Min (days	CV (%)	SD (days	Max (days	Mean (days	Min (days	CV (%)	SD (days
RCP 4.5_CSIRO	25	23	22	5	1	28	27	25	4	1
RCP4.5_Had	25	23	21	4	1	32	32	29	4	1
RCP4.5_MIROC	26	24	22	6	1	30	30	29	2	1
	Lalibela					Srinka				
RCP 4.5_CSIRO	26	24	18	10	2	20	22	24	2	1
RCP4.5_Had	26	23	18	10	2	23	26	28	6	2
RCP4.5_MIROC	23	22	21	3	1	21	23	25	5	1
	NDD									
	Kombolcha					Kobo				
RCP 4.5_CSIRO	97	97	97	1	1	96	93	92	1	1
RCP4.5_Had	99	97	95	1	1	90	87	86	2	1
RCP4.5_MIROC	98	96	95	2	2	91	90	89	1	1
	Lalibela					Srinka				
RCP 4.5_CSIRO	98	96	94	2	2	100	98	96	1	1
RCP4.5_Had	100	97	94	2	2	97	94	92	2	2
RCP4.5_MIROC	99	98	97	1		99	97	95	1	1

NB: NRD is number of rainy days, NDD is number of dry days, CV is coefficient of variation and SD is standard deviation

4.2.4. Projected trends in future annual rainfall totals

Future trends in annual rainfall totals by 2030s under RCP4.5 emission scenario predicted by three GCMs (CSIRO, Had and MIROC) is presented in Table 17. Future prediction of annual rainfall totals indicated that non-significant increasing trend will be expected at all the studied stations, except at Srinka non-significant decreasing trend will be observed by 2030s. But when we looked in to the trend prediction by each GCM, the CSIRO model predicted decreasing trends in annual rainfall totals over all studied the stations being significant at 0.05 over Kombolcha and Srinka while significant at 0.01 over Kobo stations. On the other hand, the Had model predicted increasing trends in annual rainfall totals over Kobolcha, Kobo and Srinka and conversely a decreasing trend at Lalibela with the predicted trends being significant at 0.05 significance level over Kombolcha and Lalibela stations. Similarly the MIROC model predicted statistically significant increasing trends over Kobolcha and Kobo at 0.01 and over Lalibela at 0.05 significance levels. Conversely, MIROC model predicted, strong significance decreasing trend in future annual rainfall over Srinka. This shows that, two of the three GCMs (namely the CSIRO and the MIROC) agreed on the prediction of significant decreasing trend of future annual rain fall total at Srinka. Similarly, the Had and the MIROC models agreed in prediction of significant increasing trend of future annual rainfall totals at Kombolcha. The significant increasing trend in annual rainfall totals is projected at Kombolcha and conversely significant decreasing trend in annual rainfall totals is projected at Srinka whereas, at the rest of the stations the prediction is mixed. The projected significant increasing and declining changes need attention regarding to wter logy and drought occurrence, respectively, by 2030s over the study area.

Table 17 . Projected trends with uncertainty of models prediction in annual rainfall totals for 2030s (2021-2040) under RCP4.5 emission scenario by SCIRO, Had and MIROC models at four stations in the North Eastern Amhara, Ethiopia.

Years	Stations							
	Kombolcha		Kobo		Lalibela		Srinka	
2030s	Parameters							
	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q
RCP 4.5_CSIRO	-2.56*	-3.4	-3.90***	-3.54	-0.03	-0.153	-2.17*	-3.97
RCP4.5_Had	2.37*	3.25	1.30	0.06	-2.08*	-2.11	0.88	2.92
RCP4.5_MIROC	5.22***	5.98	5.03***	7.72	2.2*	3.6	-4.48***	-8.46

NB: * is Significant at 0.05 and *** significant at 0.001. Z_{MK} is Man Kendall trend test and Q is slope

4.2.5. Projected trends in seasonal rainfall totals

Trend analysis in seasonal rainfall totals by 2030s under RCP4.5 emission scenario as predicted by three GCMs (CSIRO, Had and MIROC) is also shown in Table 18. Similar to that of the annual rainfall totals, GCMs predicted significant increasing trend in future seasonal Kiremt rainfall totals at 0.01 over all the studied stations. When we looked in to the GCMs prediction, CSIRO model predicted significant increasing trend in *Kiremt* season rainfall over Lalibela and Srinka. On the other hand, the Had model predicted increasing trends at Kombolcha, Kobo and Srinka and conversely a decreasing trend at Lalibela with the predicted trends being significant at Kombolcha and Kobo. Similarly, the MIROC model predicted significantly increasing trends of the *Kiremt* rainfall total at all locations. This shows that, among the three models the CSIRO and the MIROC models agreed in prediction of significant increasing trends in seasonal *Kiremt* rainfall total at Lalibela and Srinka. Moreover, the Had and the MIROC models agreed on prediction of significant increasing trends in seasonal *Kiremt* rainfall total at Kombolcha and Kobo by 2030s. Likewise, Hadgu *et al.* (2014) indicated that an increasing trend in future seasonal *kiremt* rainfall totals in the northern Ethiopia by 2030s. In line with this, NMA (2007) reported that the future *kiremt* season may experience increment in rainfall amount at different places in Ethiopia by 2030s and 2050s.

With regard to *Belg* season rainfall totals, declining trend is projected at all the studied stations with statistically significant at 0.01 and 0.001 over Kobo and Srinka, respectively. When we looked in to the predictions, GCMs varied in prediction of future *Belg* rainfall trends over the study area by 2030s. For instance, the CSIRO model predicted decreasing trends in seasonal *Belg* rainfall totals over all the stations with trends being significant at 0.001 over Kobo and Srinka. On the other hand, the Had model predicted significant decreasing trends in future *Belg* rainfall totals at 0.01 over Kobo and at 0.05 significance levels over Lalibela. Similarly, the MIROC model predicted decreasing trends in the future seasonal *Belg* rainfall totals over Kombolcha, Kobo and Srinka and conversely increasing trend at Lalibela with trends being significant only over Srinka at 0.001. This shows that, among the three models the CSIRO and the Had agreed in prediction of significant decreasing trends in seasonal *Belg* rainfall total at Kobo. Similarly CSIRO and the MIROC agreed on prediction of significant decreasing trends of future seasonal *Belg* rainfall total at Srinka.

In general, the future *Belg* season rainfall will be expected to have decreasing trend over the North Eastern Amhara by 2030 and, this implies that the study area will face challenge in future *Belg* growing season regarding to rainfall amount. All the projected information (variability in amount, LGS, NRD, NDD, declining trend) for future *Belg* season indicates that this season will be risky for rain fed crop production by 2030s. In line with this, Hadgu *et al*. (2014) reported the decreasing trend in *Belg* rainfall totals in the future at the northern Ethiopia. And Kassie *et al.* (2014) again noted that *Belg* season will experience decreasing trend in rainfall. Therefore, decision makers need to use seasonal oriented climate information enable to take timely and appropriate measure in case of sowing, harvesting, and cop selection to be planted or to plan non-farm practices.

Table 18. Projected trends in future seasonal *Kiremt* and *Belg* rainfall totals for 2030s (2021-2040) under RCP4.5 emission scenario as predicted by three models at four stations in the North Eastern Amhara, Ethiopia.

Year_2030s	Stations							
	Kombolcha				Kobo			
	Kiremt		*Belg*		*Kiremt*		*Belg*	
	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q
RCP 4.5_CSIRO	-0.91	-0.58	-0.65	-0.60	1.07	0.24	-6.04***	-1.08
RCP4.5_Had	3.77***	0.32	0.84	1.38	2.65**	0.08	-2.74**	-0.02
RCP4.5_MIROC	4.90***	4.36	-0.58	-0.20	5.22***	5.65	-0.81	-0.19
	Lalibela				Srinka			
RCP 4.5_CSIRO	2.43*	1.12	-0.49	-0.81	2.27*	2.29	-4.51***	-1.27
RCP4.5_Had	-0.32	-0.27	-2.40*	-3.45	1.78	0.53	0.00	0.00
RCP4.5_MIRC	5.63***	0.47	0.13	0.26	4.54***	2.67	-5.97***	-6.67

NB: *Significant at 0.05, ** significant at 0.01 and *** significant at 0.001. Z_{MK} is Man Kendall trend test and Q is slope

4.2.6. Changes with uncertainties of models prediction in rainfall characteristics

4.2.6.1.Seasonal number of rainy days

Comparing with the base period (1992-2012), the predicted change with the uncertainty of models prediction in NRD for future *Kiremt* and *Belg* growing seasons by 2030s (2021-2040) under RCP4.5 emission scenario at four stations in the North Eastern Amhara is shown in Figure 10. In addition to the Figure 10, the prediction of change in NRD under each GCMs (CSIRO, Had and MIROC), is shown in Appendix Figure 2 and 3.

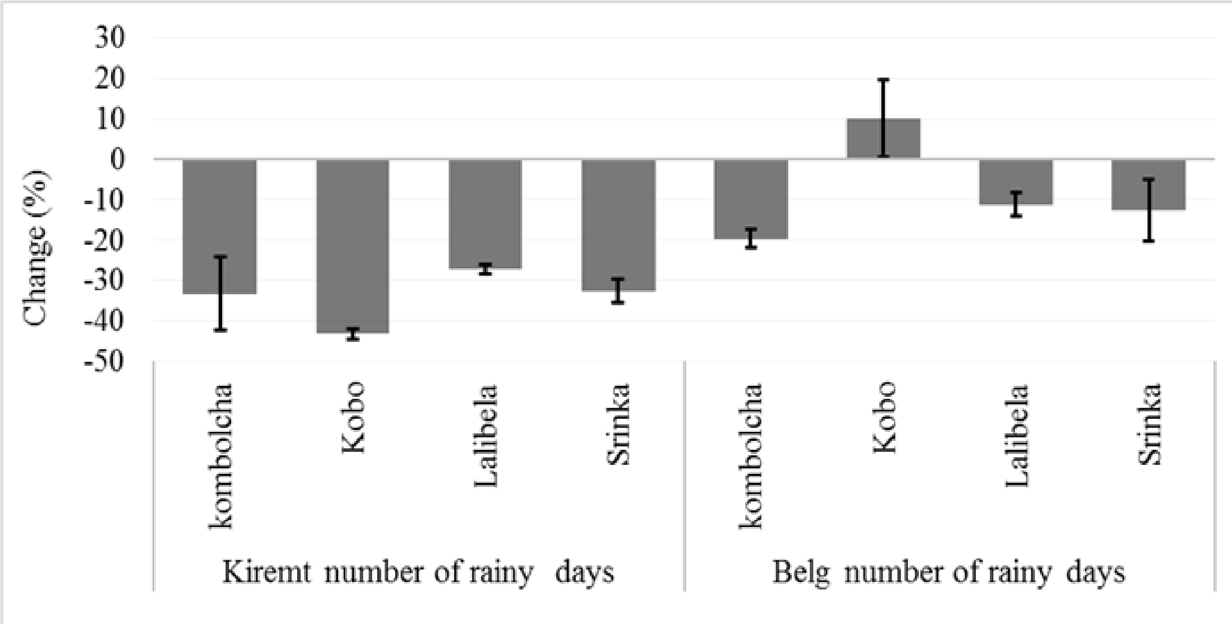

Figure 10. Changes with uncertainty of models prediction in seasonal number of rainy days by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models relative to base period (1992-2012) at four stations in the North Eastern Amhara, Ethiopia.

When we looked into the percentage change in NRDs for future *Kiremt* growing season relative to the base period, Kobo, Lalibela and Srinka stations will have decreasing change with less uncertainty of models prediction, being in the range of 27.3 ± 1% at Lalibela to 43.3 ± 1% at Kobo by 2030s. Moreover, the projected changes in NRDs for future *Belg* growing season showed decreasing change with less uncertainty of models prediction at Kombolcha and Lalibela stations.

combining the information from the projected increasing change in future *Kiremt* rainfall totals (Figure 12) with projected decreasing change in NRD for the same season (Figure 10) indicates that the future *Kiremt* season rainfall will have waterlogging or flood occurrence over Kobo, Lalibela and Srinka stations, most probably the event will occur at the month of July by 2030s . This will have negative impact on future rain fed crop production in the study area if local farmers could not change the projected maximum rainfall during the month of July and August in to opportunity. Rain water harvesting may be possible in the future month of July to use as supplemental irrigation in the month of September as it is projected to be dry in the future in turn long cycle crops may be possible to be planted in North Eastern Amhara by 2030s.

4.2.6.2.Seasonal number of dry days

Relative to the base period (1992-2012), the projected change with uncertainties of models prediction in number of dry days (NDD) for the future *Kiremt* and *Belg* growing seasons is depicted in Figure 11 and Appendix Figure 2 and 3. When we looked in to the percentage change in NDD over the base period, an increasing change will be expected at all the studied stations during the *Kiremt* growing season by 2030s. The projected increasing change in future *Kiremt* NDD will be in the range of 27.7 ± 1% at Kobo to 31.1 ± 1.5% at Kombolcha. The predicted increasing change in NDD indicates that in the future main rain season (*Kiremt*) rain fed crop production will face challenge of moisture stress in the North Eastern Amhara by 2030s.

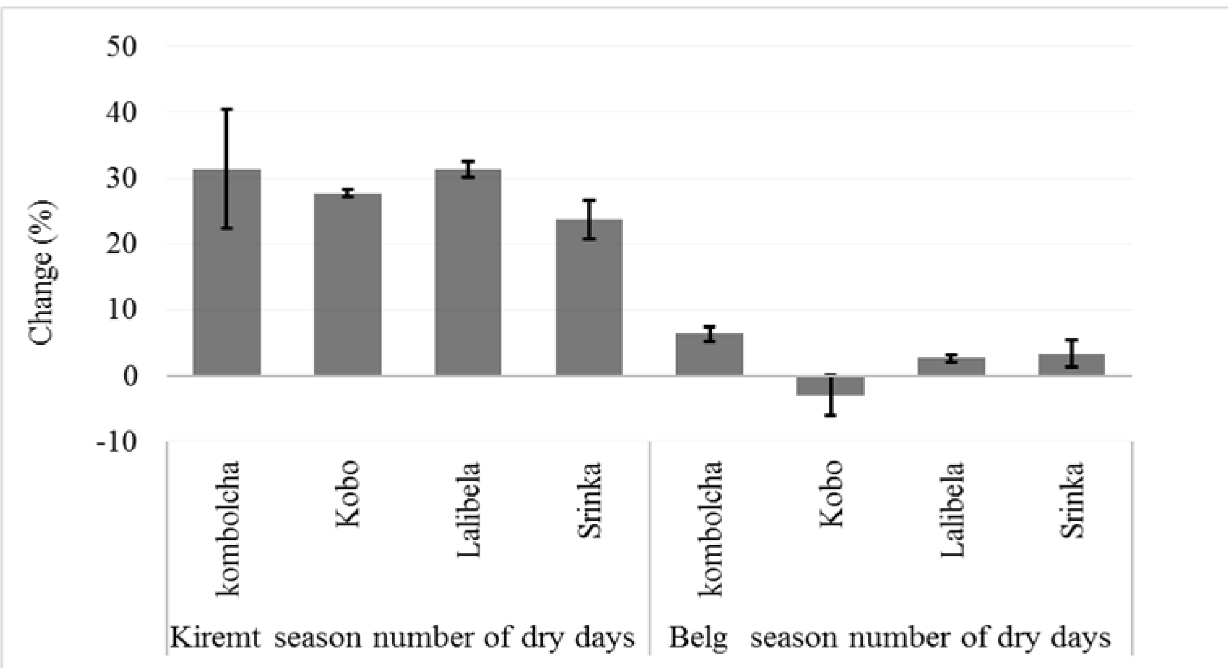

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Figure 11. Changes with uncertainties of models prediction in seasonal number of dry days for 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models relative a base period (1992-2012) in the North Eastern Amhara, Ethiopia.

On the other hand, the predicted percentage change in NDD for future *Belg* growing season will be increasing at most of the studied stations by 2030s. For the *Belg* season, however, a slight reduction in NDD is predicted at Kobo with relatively higher uncertainty of models prediction (Figure 11).

This implies that by 2030s (2021-2040) there will be high probability of increasing in NDD for both the *Kiremt* and the *Belg* seasons in the study area. Consequently, the predicted increasing change in NDD will have a negative impact on rain fed crop production due to increasing evaporation and decreasing availability of water, and there by taking the opportunity of days being rain

4.2.6.3. Rainfall patterns relative to the base period

Future rainfall pattern and its average projected change relative to the base period (1992-2012) at four stations in the North Eastern Amhara is presented and discussed in Figure 12 and Appendix Figure 4. According to the Figure 12 and Appendix Figure 4, the study area will continue to have *Kiremt* dominated two rainfall seasons (quasi bi-modal) by 2030s (2021-2040) as predicted on average by the three GCMs (CSIRO Mk 3-6-0, Had GEM2-ES and MIROC-ESM-CHEM). All GCMs agreed that the month of July followed by month of August will have the maximum peak rainfall at all the studied stations by 2030s over the study area. From the projected pattern, the month of September is expected to be dry at Kombolcha, Lalibela and Srinka except, some progress is projected at Kobo. In a similar way, all GCMs predicted that month of June will be dry at all the studied stations by 2030s. The future *Belg* rainfall will be expected to have more variable and complicated pattern as depicted in Figure 12. Relative to the observed pattern, the rainfall over the month of March will reduce at Kombolcha and Srinka but, a tendency of increasing is predicted at Kobo and Lalibela for the same month by 2030s. In case of month of April, predictions indicated that the future *Belg* rainfall will reduce at Kombolcha and Srinka stations relative to the base period pattern. All the studied stations are projected to receive future *Belg* season rainfall progressively starting from the month of May. From agricultural point of view, the future *Belg* season is projected to be risky for the North Eastern Amhara Region by 2030s. As can be seen in Figure 12, over all the studied stations *Belg* rainfall is projected to shift forward and/or diminish. In line with this, Hadgu *et al*. (2014) also reported similar expected forward shifting of future *Belg* season among nearby stations of Tigray Region. According to Kassie *et al*. (2014), no more rain fed crop production in the future *Belg* season. If the projected dry months of June and September treated well by supplemental irrigation, long cycle crops can be planted in the study area by 2030s. The source of water for supplemental irrigation for the month of September may be from rain water harvesting during the month of July.

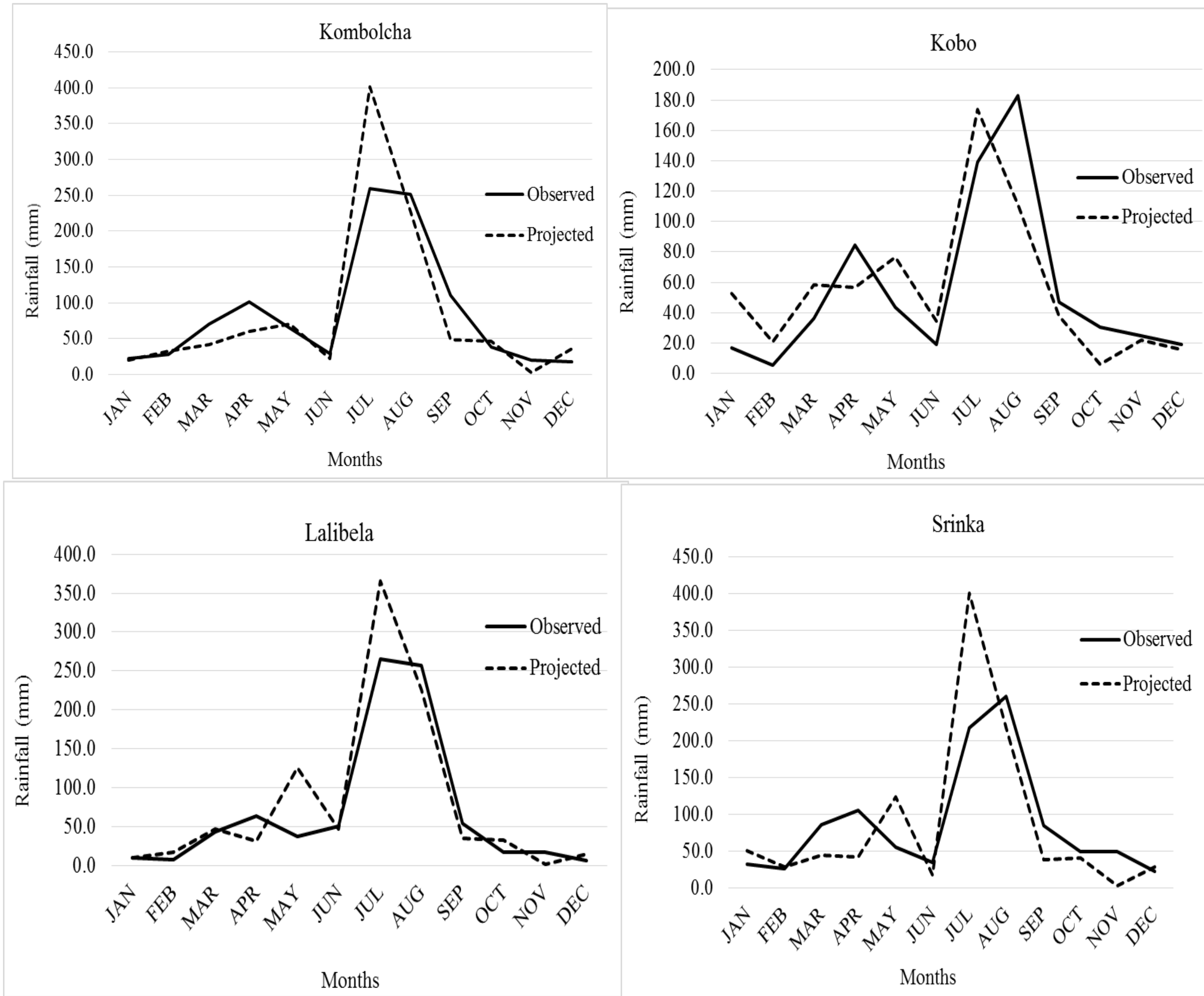

Figure 12. Future rainfall patterns for 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models relative to base period (1992-2012) in the North Eastern Amhara, Ethiopia.

4.2.6.4.Changes with uncertainties of models prediction in annual rainfall totals

Relative to the base period (1992-2012), the future change in total annual rainfall with uncertainties of models prediction is shown in Figure 13 and Appendix Figure 4. In the present study, the projected total annual rainfall is predicted by GCMs (CSIRO, Had and MIROC) to vary from stations to stations by 2030s. For instance, at Kombolcha GCMs showed decreasing change with high uncertainty of models prediction whereas, at Kobo, Lalibela and Srinka GCMs indicated an increasing change with low uncertainty of models prediction except, high uncertainty of models prediction will be expected at Lalibela. When we looked in to the percentage change with the uncertainty of models prediction of annual rainfall totals will decrease by 1.1 ± 7.0 % at Kombolcha, but will increase by 5.6 ± 2.5 %, Kobo; by 17.7 ± 15.0 % at Lalibela and by 4.1 ± 2.0 % at Srinka by 2030s in the North Eastern Amhara.

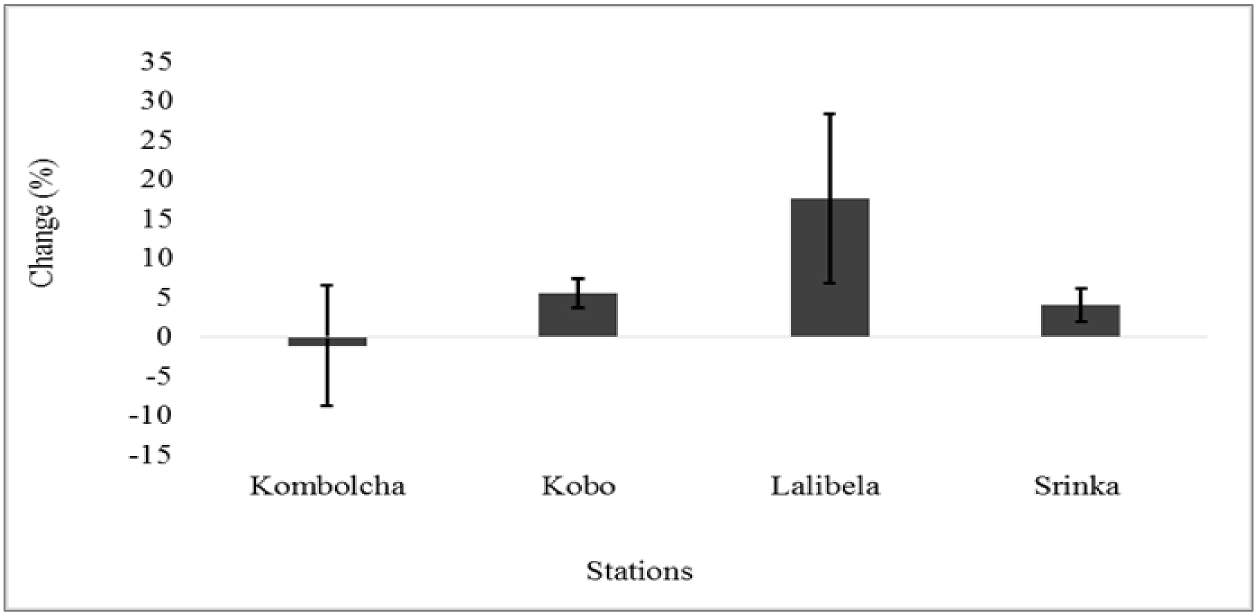

Figure 13. Changes with uncertainties of models prediction in annual rainfall totals for 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models relative to base period (1992-2012) in the North Eastern Amhara, Ethiopia.

Thus, the change in future annual rainfall totals can be both a threat and an opportunities for North-Eastern Amhara by 2030s. It will be a threat for Kombolcha because of the predicted decrease in total rainfall, but an opportunities for Kobo, Lalibela and Srinka because of the projected rainfall increase. In line with the present result, Hadgu *et al*. (2014) noticed that the future annual rainfall will have both threat and opportunity depending on stations studied in the Northern Ethiopia. Moreover, NMA (2007) indicated that annual rainfall will show a tendency of increasing over Ethiopia by 2030s, 2050s and 2080s.

4.2.6.5.Changes with uncertainties of models prediction in future seasonal rainfall totals

Uncertainty of predictions by GCMs (CSIRO, Had and MIROC) of the total seasonal rainfall and the average predicted change by 2030s relative to the base period (1992-2012) at four stations is shown in Figure 14 and Appendix Figure 5. As shown in the figure 14, uncertainty of models prediction of future seasonal rainfall totals over North-Eastern Amhara is higher for the *Belg* than the future *Kiremt* season. By 2030s (2021-2040), the seasonal *Kiremt* rainfall total is projected to decrease at Kobo over the base period.

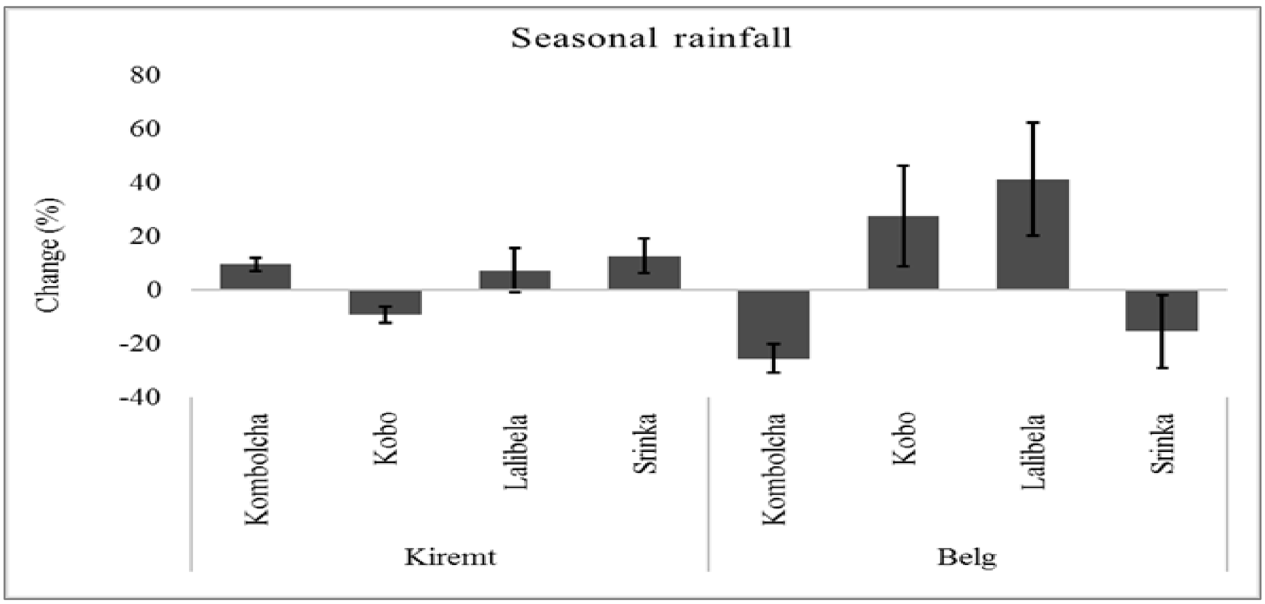

Figure 14. Changes with uncertainties of models prediction in seasonal rainfall totals for 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models relative to base period (1992-2012) in the North Eastern Amhara, Ethiopia.

The *Belg* rainfall total is also expected to decrease at Kombolcha and Srinka stations. Conversely, for Lalibela and Srinka stations, both the seasonal *Kiremt* and the *Belg* total rainfall for 2021-2040 is predicted to increase over the base period. The decreasing change in main rain season (*Kiremt*) rainfall totals at Kobo and in small rain season (*Belg*) rainfall totals at Kombolcah and Srinka could be a threat, while an increase change in *Kiremt* rainfall totals at Kombolcha, Lalibela and Srinka and in *Belg* rainfall totals at Kobo and Lalibela could be opportunity for the study area by 2030s. The same result was reported by different authors that the future main rain season (*Kiremt)* will have increasing change (NMA, 2007; Hadgu *et al*., 2014; Kassie *et al*., 2014) whereas, future *Belg* will experience decreasing change over Ethiopia and over the Northern part of Ethiopia.

4.2.6.6.Changes with uncertainties of models prediction in start and end date of *Kiremt* growing season

The average projected change in start (SOS) and end date (EOS) of *Kiremt* growing season relative to the base period (1992-2012), with the uncertainties of models prediction by 2030s at four stations is depicted in Figure 15. The projection out puts by CSIRO, Had and MIROC GCMs under RCP4.5 emission scenario is found in Appendix Figure 6. Relative to the base period, mean SOS of *Kiremt* growing season at the four stations are projected to decrease. The declining change in SOS indicates early entrance of *Kiremt* rainfall across the study area by 2030s. However, the percentage change in *Kiremt* SOS relative to the base period with the observed uncertainties of models prediction showed variation among stations in the North Eastern Amhara. For instance, the uncertainty of models prediction at Kombolcha, Kobo and Srinka is relatively higher, and conversely less at Lalibela. Although the projected change in SOS of *Kiremt* growing season is small (1.6 ±3.0 % at Srinka to 3±3.0 % at Kobo) with less uncertainty of models prediction, it shows a tendency of early SOS of the *Kiremt* growing season relative to the base period mean SOS across the study area by 2030s. The projected early SOS may be due to the backward shifting of main rain (*Kiremt*) season (Figure 12).

On the other hand, the projected change with uncertainties of models prediction in end date (EOS) of *Kiremt* growing season, decreasing change is projected at all the studied stations in the North Eastern Amhara by 2030s (Figure 15). The projected declining change indicates that the EOS of future *Kiremt* growing season will terminates early relative to the mean EOS of the base period (1992-2012). The uncertainty of models prediction will be less at three of the four stations (Figure 15). The predicted percentage of change in EOS with the uncertainty of models prediction will vary from 3.9±2% at Labella to 11.6±1% at Srinka over the study area. The projected relatively high early cessation of future *Kiremt* growing season will have an effect on length of growing season (LGS) by shortening the duration of growing season, and this will result in rain fed crop yield reduction by 2030s. In related to the present result, Thornton *et al.* (2006) indicated that in much of the regions across Eastern Africa including Ethiopia, there will be little to moderate reduction in the length of the growing period (< 20%), and in some areas the reduction will be more severe (>20%).

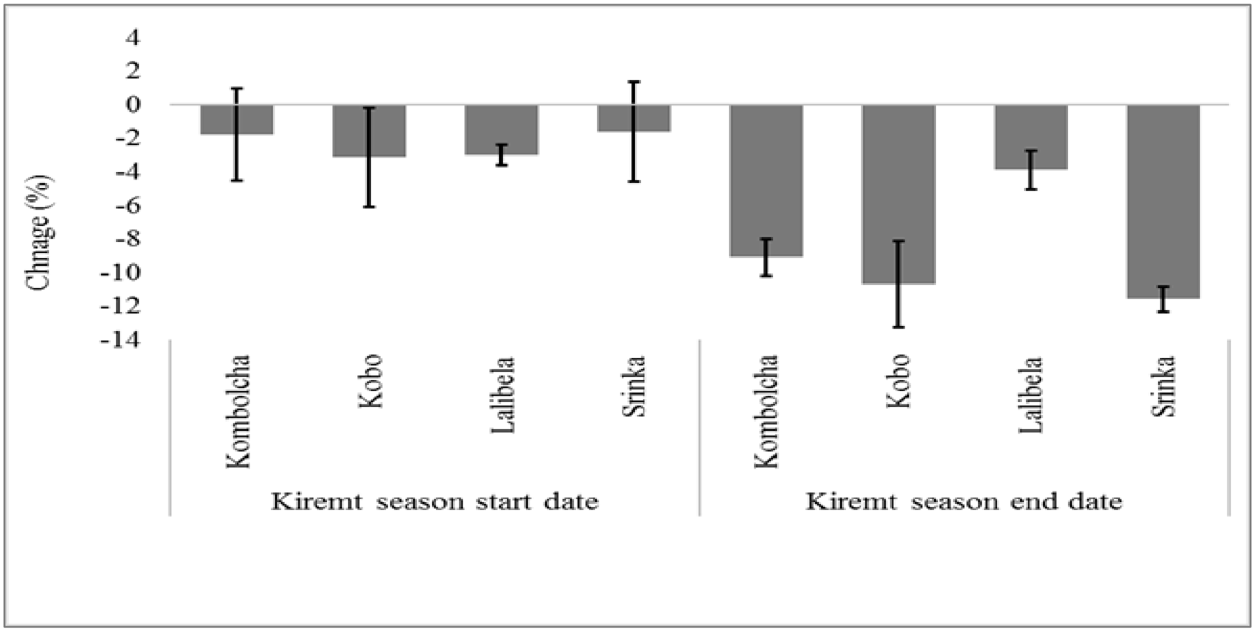

Figure 15. Changes with uncertainties of model prediction in start and end date of *Kiremt* growing season for 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models relative to base period (1992-2012) in the North Eastern Amhara, Ethiopia

4.2.6.7.Changes with uncertainties of models prediction in start and end date of *Belg* growing season

The projected change in start (SOS) and end date (EOS) of future *Belg* growing season with the uncertainties models prediction by 2030s at four stations is given in Figure 16. The GCMs (CSIRO, Had and MIROC) predictions is found in Appendix Figure 7 (a) and (b) separately. Relative to the mean SOS of the base period (1992-2012), the future (2021-2040) SOS of *Belg* growing season showed an increasing change with less uncertainty. This shows that the future *Belg* season will start lately by 2030s at four stations over the base period. The projected percentage change of the SOS for *Belg* season over the base period, varies from 28 ± 9% at Kobo to 52±4% at Lalibela stations. The projected increasing change in SOS with less uncertainty of models prediction implies that the future *Belg* season will be characterized by late start so that the length of growing season will be very short. The same findings were reported by Kassie et *al*. (2014) and Hadgu *et al*. (2013) that

Belg growing season will shift forward and as a result will become less important for rain fed crop production by 2030s and 2050s.

On the other hand, on average the GCMs (CSIRO, Had and MIROC) projected an increasing change in end date (EOS) for future *Belg* growing season with less uncertainty at Kombolcha and Srinka stations whereas, with relatively high uncertainty at Kobo and Lalibela by 2030s. Relative to the base period (1992-2012), the percentage change in the end date of *Belg* growing season will vary from 34±10% at Lalibela to 47±5% at Kobo. In general, the projected late SOS for future *Belg* growing season will have negative impact on length of growing which result in reduction of rain fed crop production by 2030s over the study area. Whereas, the projected late EOS will have positive impact to lengthen length of growing season and in turn good for crop production in the study area. However, as the average increasing change in SOS for *Belg* growing season will be high, the length of *Belg* growing season is projected to be very short by 2030s (Table 14 and Figure 12). The same finding was reported by Thornton *et al.* (2006) over Africa, including Ethiopia that the length of growing season will decrease in the future.

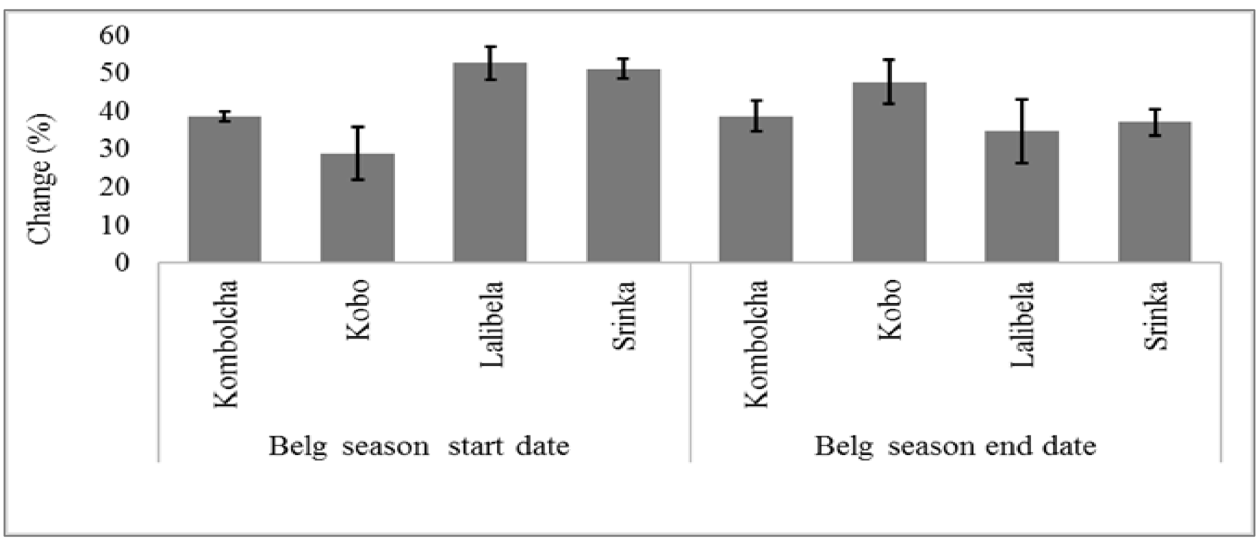

Figure 16. Changes with uncertainties of models prediction in start and end date of *Belg* growing season for 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models relative to base period (1992-2012) in the North Eastern Amhara, Ethiopia

4.2.6.8. Changes with uncertainties of models prediction in *Kiremt* and *Belg* length of growing seasons

The projected change in the length of future *Kiremt* and *Belg* growing seasons (LGS) with uncertainties of models prediction for 2030s at four stations is depicted in Figure 18 and Appendix Figure 8. All the three GCMs (CSIRO, Had and MIROC) predicted decreasing change in LGS for both *Kiremt* and *Belg* growing seasons at all the studied stations in the North Eastern Amhara by 2030s. The predicted length of *Kiremt* and *Belg* growing seasons (by 2021-2040) over the base period (1992-2012), is projected to vary from station to station. For instance, the projected change in future LGS at Kombolcha, Kobo, Lalibela and Srinka stations showed low uncertainty for both the *Kiremt* and the *Belg* growing seasons. Conversely, relatively high uncertainties of models prediction for the *Belg* season is projected at Lalibela. When we look in to the percentage change in LGS for both seasons, the declining change will vary from 5.8± 1% at Lalibela to 25.4±0.5% at Srinka for *Kiremt*, and from 32.9±2% at Kobo to 51.2±3% at Lalibela stations for the *Belg* growing season by 2030s. Hence, the projected change in the future LGS for both the *Kiremt* and the *Belg* seasons could result in shortening of length of growing season and that could be a threat to rain fed crop production in study area. Previous researchers also reported similar projection of decreasing change in length of future growing seasons. For instance, Hadgu *at al*. (2014) reported decreasing change in LGS in the northern Ethiopia. Thornton *et al.* (2006) found that in much of the regions across Africa including Ethiopia, there will be little to moderate reduction in the length of the growing period (< 20%) with more severe reduction in some areas (>20%).

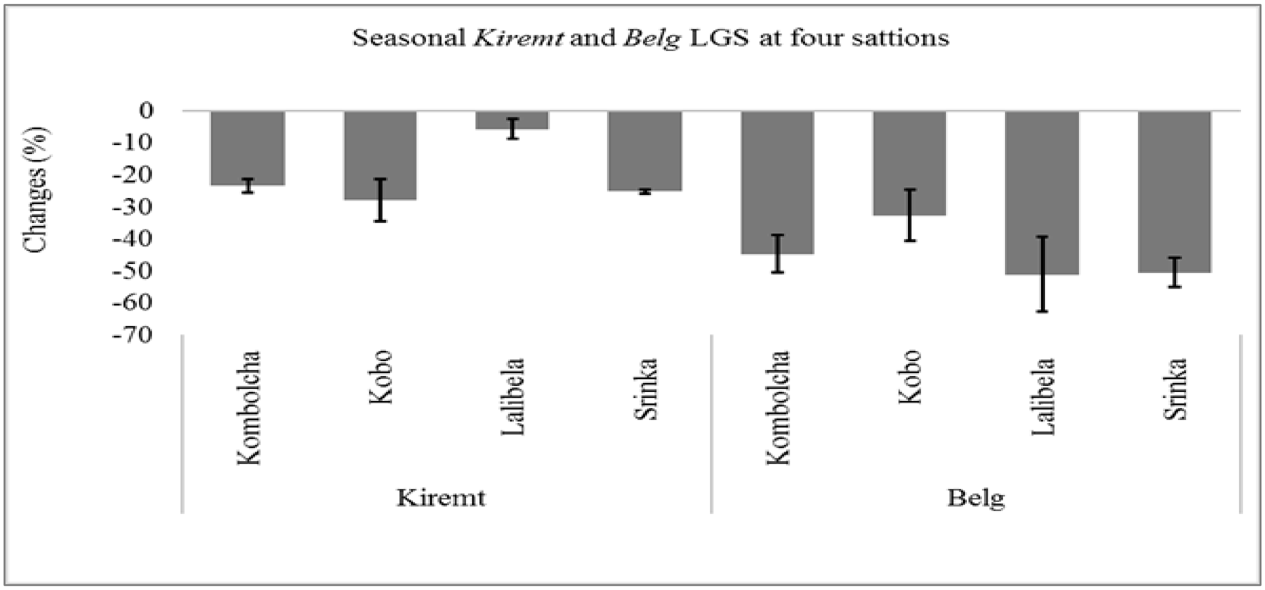

Figure 17. Changes with uncertainties of model prediction in length of *Kiremt* and *Belg* growing season for 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models relative to base period (1992-2012) in the North Eastern Amhara, Ethiopia.

4.3. Implications of Rainfall Variability Risk on Crop Production

Rain fed crop production is strongly influenced by weather and climate change (Taye *et al*., 2012). Smallholder farmers in Ethiopia, including in the North Eastern Amhara, have been facing severe climate related hazards (Seleshi and Zanke 2004). The variable rainfall and the frequent occurrence of drought in the study area have negatively affected livelihoods of rural households (Segele and Lamb, 2005; Ayalew *et al*., 2012). The ongoing and the future anticipated climate change is expected to aggravate and worsen some of the challenges facing the farming community and also impose new risks and challenges beyond the range of current experiences and adaptation options. This section discussed implications of observed (1992-2012) and predicted (2021-2040) rainfall variability and changes risks for rain fed crop production in the North Eastern Amhara Region.

4.3.1. Implications of observed variability risk on rain fed crop production

The amount and distribution of rainfall is generally the most important determinants of inter-annual rainfall fluctuations and intra seasonal of rainfall indices that in turn results in fluctuations in rain fed crop production in Ethiopia (Bewket and Conway, 2007; Araya and Stroosnijder, 2011; Conway and Schipper, 2011). As being part of the country, the North Eastern Amhara Region is the most vulnerable region to recurrent drought in Ethiopian history (Ayalew *et al*., 2012). In the present study, the past seasonal *Kiremt* and the seasonal *Belg* rainfall amounts, over the North Eastern Amhara Region, were observed being small, less stable and variable during the study period (1992-2012). The observed standard deviation (SD) and coefficient of variation (CV) values for the annual and seasonal *Kiremt* and seasonal *Belg* rainfall totals were observed being in the range of 94mm to 130.5mm and 12-13% to 85mm to 106.8mm and 14- 22% and from 49mm to 103mm and 28.4 – 30%, respectively. The observed decreasing trend, small amount, high variability and less stability of the past seasonal *Belg* rainfall totals and observed start date failure (33-66%) indicated that this season was highly risk full for rain fed crop production across the study area. Moreover, the length of the *Kiremt* and the *Belg* growing seasons showed decreasing trends at all the stations studied during the study period. Various authors reported that the length of growing season shows decreasing trend in the North Eastern Ethiopia. For instance, Ayalew *et al*.(2012), Taye *et al*.(2013), Hadgu *et al*. (2013) and Kassie *et al*.(2014) reported decreasing trends in Length of growing season because of late onset and early end date of the growing seasons . The observed dry spell occurrence at greater than 10 days length was above 10% at Kombolcha and Kobo, 30% at Lalibela and Srinka during the past *Kiremt* season. on the other hand, the observed probability of dry spell occurrence at greater than 5 and 7 days length were observed being above 80% , 40% , 90% and 70% at Kombolcha, Kobo, Lalibela and Srinka, respectively, during the *Belg* season. Moreover, the occurrence of dry spells at greater than 15 days length increases rapidly after 60 days from successful planting date is established at Kombolcha and Srinka and, after 50 days from successful planting date is established at Lalibela and Kobo.

Therefore, the observed small and unstable rainfall amount in the region associated with decreasing trends in length of growing season, increasing trends in number of dry days, and high probability of dry spells occurrence in observed crop growing seasons implies that rain fed crop production in the region was highly challenged during 1992-2012. The observed high variability and declining trends in *Belg* rainfall amount was disadvantages for rain fed long maturing crops for the last 21 years at the study area. The observed crop failure in the seasonal *Belg* growing season was very high being in the range of 33% to 66% due to onset date growing season failure. Large variability of *Belg* rainfall already makes this season unsuitable for rain fed crop production (Rosell, 2011). Araya and Stroosnijder (2011) and Hadgu *et al*. (2013) reported that long maturing crops (e.g.

Sorghum) in northern Ethiopia are at risk. Earlier studies also provided evidence that uncertainty of the start date, end date and length of growing seasons are the main challenges for rain fed crop production. The World Bank (2006), for instance, reported that the late start of the *Kiremt* growing season *in* 1997 caused a reduction in average yield of cereals by 10% across Ethiopia.

The length of growing season and its reliability determines the suitability of crops and/or cultivars that can be cultivated in a given area and is an important indicator of yield potentials (Jaetzold and Kutsch, 1982). The length of the growing seasons in the North Eastern Amhara Region exhibits shorter because of the late start and the early end date of growing seasons. The North Eastern Amhara Region was further characterized by the recurrent dry spells occurrence with higher probabilities during the growing seasons. Because of this, most of the rain fed crops cultivated in the region were most likely to be exposed to moisture stress. Earlier studies by Segele and Lamb (2005) and Araya and Stroosnijder (2011) also indicated that dry spells of about 10 days length is one of the major causes of crop failure in rain fed farming systems of Ethiopia. In general, the *Belg* growing season had higher probability of dry spells than the seasonal *Kiremt* growing season during the period of the study (Figure 8). Generally, rain fed crop production over the past 21 years was highly challenged by less stable rainfall distribution, high dry spell occurrence, late onset and early end date of the growing seasons. Rain fed long maturing crops were at risk of short length of growing seasons and even short maturing period rain fed crops were at risk of high dry spell occurrence which resulted in water stress in the study area.

4.3.2. Implications of the future variability risk for rain fed crop production

Global Circulation Models (CSIRO, Had and MIROC) projections in future intra seasonal rainfall conditions suggest that annual rainfall totals will be expected to increase by 2030s under RCP4.5 emission scenario at most of the studied stations. On average the predicted future *Kiremt* rainfall totals will be expected to increase at all the stations studied with statistically significant at 0.01 significance level. Projected rainfall totals for the future *Belg* season showed decreasing trend at all the studied stations but, significant at 0.01 and 0.001 significance levels over Kobo and Srinka, respectively. In line with the present study result, Hadgu *et al*. (2014) reported that there will be a decrease in the future seasonal *Belg* rainfall by 28-48% for 2030s in the nearby stations of the present study area. Associated with the projected declining trends of seasonal *Belg* rainfall amount and increasing change in number of dry days, the projected start date of future *Belg* growing season will be late by 2030s over the study area. All the three GCMs used in the present study projected decreasing change in future length of growing season with less uncertainty of models prediction for both the *Kiremt* and the *Belg* growing seasons. The decreasing change in length of growing season is projected being in the range of 5.8 ±1% to 27.9 ± 0.5% for the *Kiremt* and from 32.9 ± 2% to 51.2 ± 3% for the *Belg* seasons over the north eastern Amhara for 2030s. As a result of these, the *Belg* growing season will not be satisfactory for rain fed crop production in the future at all studied stations even for drought resistance crops. The projected length of the *Belg* growing season for 2030s is predicted to be in the range of 28 days at Lalibela to 54 days at Kobo, and this is not suitable for rain fed crop production in the region. The declining trends of the *Belg* rainfall might have also a significant adverse effect on the farming practices of the area as it may limit crop choice and enhance loss of biodiversity. Kassie *et al*. (2014) reported that no more crop production in the future might be possible during the future *Belg* growing season. Other reports on future rainfall projections for Ethiopia also support the present result. For instance, Arndt *et al*. (2011) indicated that the *Belg* rainfall will be declining by 5-6% in 2080s relative to the 1960-1990 period. Thornton *et al*. (2006) also reported that in much of the regions across Africa including Ethiopia, there will be little to moderate reduction in the length of the growing period (< 20%) and in some parts the reduction will be more severe (>20%). Moreover, the three GCMs used in the present study agreed to predict an increasing rainfall totals and decreasing in rain days for future *Kiremt* season at the majority of the studied stations. Consequently, this indicates that the future *Kiremt* season rainfall will concentrate at some months, probably at month of July, as predicted by all GCMs on average, as a result combined with high soil water holding capacity (Vertisols) in the North Eastern Amhara, the projected increase in future rainfall of month of July will cause water logy or flood that affects crop production in the study area. However, the projected maximum rainfall amount during month of July will be used as supplemental irrigation water for the predicted dry month of September by 2030s.

On the other hand, the projected declining trend in seasonal *Belg* rainfall totals, length of the growing seasons and high probability of seasonal dry spells altogether indicate that an increasing risk for rain fed crop production in the North Eastern Amhara Region by 2030s. Short growing seasons (*Belg*) due to a delayed start date of the growing season hampers soil preparation, exposes crops to increased terminal moisture stress during grain filling and reduce crop yields. Rain fed crop production in the North Eastern Amhara- already impacted by the current rainfall variability- is likely to be further aggravated challenged by 2030s (2021-2040).

5. SUMMARY, CONCLUSION AND RECOMMENDATION

5.1. Summary and Conclusion

Information on seasonal *Kiremt* and seasonal *Belg* rainfall amount is important in the rain fed agriculture of Ethiopia since more than 85% of the population is dependent on agriculture particularly on rain fed farming practices (Tuffa, 2012). Due to seasonal rainfall variability, the country in general and the North Eastern Amhara Region in particular, becomes vulnerable to recurrent droughts and to rain fed crop failures (Viste *et al*., 2012; Taye *et al*., 2013). As a result analysis of intra seasonal rainfall variability and its trend were found to be crucial for agricultural planning and water management practices (Hadgu *et al*., 2013). In response to this, the present study aimed at characterizing past and future intra-seasonal rainfall indices, analyze intra-seasonal rainfall variability, examine its trends in terms of rainfall totals, length of growing season, dry spell length, rainy and dry days and discuss the associated implications of variability risk for rain fed crop production in the North Eastern Amhara Region. Daily rainfall data at four stations from the observed rain gauge (1992-2012) and downscaled (2021-2040) under RCP4.5 emission scenario by three GCMs (CSIRO Mk.3.6.0, Had GEM2-ES and MIROC ESM CHEM) were used in the study. Coefficient of variation, and Mann Kendal trend test and Sens' slope estimator were used to study variability and trends of intra seasonal rainfall indices, respectively for the North Eastern Amhara Region.

During the study period (1992-2012), small rainfall amount, decreasing trend in rainfall amount and high CV values (28.4 – 39%) were observed in past *Belg* growing season over the North Eastern Amhara. Analysis result of annual and seasonal rainfall totals showed less stability at all the stations studied. Observed trends also indicated decreasing in rainy days and length of growing seasons, and an increasing trend in dry days is observed for both the *Kiremt* and the *Belg* growing seasons across the study area. The observed crop failure in seasonal *Belg* growing season was very high being 43% at Kombolcha, 58% at Kobo, 66% at Lalibela and 33% at Srinka due to planting date failure across the study area. The dry spell occurrence at greater than 10 days length was above 10% at Kombolcha and Kobo whereas, above 30% at Lalibela and Srinka during the past *Kiremt* growing season during the study period. on the other hand, the observed probability of dry spell occurrence at greater than 5 and 7 days lengths were observed being above 80% and 40% at

Kombolcha and Kobo and, above 90% and 70% at Lalibela and Srinka, respectively, during *Belg* growing season. Moreover, the occurrence of dry spells at greater than 15 days length increases rapidly after 60 days from successful planting date is established at Kombolcha and Srinka, and after 50 days from successful planting date is established at Lalibela and Kobo. The observed high probability of dry spells on crop calendar basis indicated that rain fed crop production over the study area was at risk of water stress for the last 21 years (1992-2012).

the GCMs(CSIRO, Had and MIROC) on average agreed in prediction of increasing change in annual and seasonal *Kiremt* rainfall totals at most of the studied stations while, decreasing change in rainfall amount is projected at all the studied stations for future *Belg* growing season by 2030s under RCP4.5 emission scenario. The projected increasing change in annual and *Kiremt* growing season and decreasing change in *Belg* growing season rainfall totals is projected to be significant at less than or equal to 0.05. When we looked in to the stability analysis of future rainfall totals, it is projected to have high SD values which indicates less stable and moderate to high variability in *Belg* rainfall for 2021-2040. The future *Belg* season will experience small rainfall amount, decreasing trend in rainfall amount, increasing in dry days, decreasing in rainy days, late start date which results very short length of *Belg* growing season. Relative to the base period mean length of growing seasons, future length of growing seasons will be shorter with less uncertainty of model prediction across the study area.

Moreover, the future *Belg* growing season will be very short, ranging from 28 days to 54 days which is not suitable for crop production in the study area. The projected forward shifting of *Belg* and the early onset of *Kiremt* growing season might be taken as an advantage for long duration crops. This will be true if the risk of dry days in month of June is managed by using irrigation. Moreover the future *Kiremt* season will experience water logy because of an increasing change in *Kiremt* rainfall totals and decreasing change in rainy days associated with the high water holding capacity of the soil in the study area.

5.2. Recommendations

Specific impact-based adaptation strategies are essential to reduce the vulnerability of rain fed crop production. To adapt the effect of intra seasonal rainfall variabilities risk on rain fed crop production, decision makers should take appropriate and available site specific options. The adaptation/mitigation options that the decision maker need to take during the risk time should consider the awareness or understanding level of farmers, availability and accessibility of options, local topography, soil, land use and land coverage. According to (Boyd *et al*., 2013), Governments across SSA, including Ethiopia, should invest heavily in early warning systems on drought and climate risk to aid farmers in planning their farming operations. Moreover, effective communication of information on climate adaptation/mitigation is essential for adaptation by households as communication increases understanding and awareness. In this regard, appropriate communication mechanisms including the use of local radio stations broadcasting in local dialect could be used to ensure that such climate information and early warnings reach the intended farmers. According to FAO (2010), the crop improvement program of Ethiopian research system has concentrated on screening early maturing varieties for drought tolerance. This is a good approach, however even during the short growing period in the dryland areas, the distribution of rainfall is highly variable within the seasons. Therefore, even a short cycle rain fed crop could be exposed to water stress at any time during its life cycle, indicating the need to develop drought resistant crops and varieties. This should be a strategy in improving rain fed crop production in the dryland areas.

Based on farmers' level of awareness and access to supplemental irrigation, they could supplement crops with irrigation water during periods of less rain. If the dry spell risks can be managed by the use of supplemental irrigation, there may be possibility to plant long maturing crops in the region by 2030s (2021-2040). Especially, the dry months of June and September need to have great attention in case of planning supplemental irrigation in the future. The source of supplemental irrigation may be different in both cases. For instance, the source of supplemental irrigation in future dry month of June may be from underground water or may be from river, depends on the availability of water and topography of the location. Whereas, the source of supplemental irrigation in the dry month of September may be from harvesting rain water as there will be high rainfall in the month of July and August by 2030s over the North Eastern Amhara. If these two projected dry months are managed, long maturing crops (e.g. sorghum) can be planted in the study area by 2030s. However, if farmers have limited access for supplemental irrigation during the time of dry periods at the beginning of growing season, they should delay sowing until the required rainfall is obtained. To manage the risk of dry spells with in the growing seasons after planting is carried out, decision makers/farmers can use agronomical practices like, mulching and thinning (*shilshalo*) to reduce moisture loss through evaporating and to reduce computation of soil water as there is dense plant in the farm. Growing quickly maturing cereal crops such as chickpea may also help to avoid complete failure because, they normally grow at the end of growing period, utilizing unused residual soil water reserves. Such crops are recommended when the seasonal rain starts too late and when there is little possibility of irrigating the crops. As a long term measure, government, policy makers and NGOs/donors should develop/assist irrigation facilities and water harvesting technologies. The information from projected decreasing change in number of rainy days and increasing change in rainfall totals during the future *Kiremt* growing season can indicate the likely hood of water logy/ flood in the study area by 2030. However, the projected maximum rainfall amount during in the future month of July can be used for supplemental irrigation for the projected dry month of September by 2030s over the study area.

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7. APPENDICES

Appendix 1. Start and end date and length of *Kiremt* growing season at four stations in the North Eastern Amhara, Ethiopia, during 1992-2012.

Indices	Statistics	Kombolcha	Kobo	Lalibela	Srinka
		Stations			
SOS	Latest (DOY)	207(jul-25)	211 (Jul-29	195(Jul-13)	195(Jul-13)
	Mean (DOY)	189(Jul-7)	191(Jul-9)	185 (Jul-3)	185(Jul-3)
	Median (DOY)	187 (jul-5)	190 (Jul-8)	187 (Jul-5)	187(Jul-5)
	Earliest (DOY)	173(Jun-21)	183(Jul-1)	167(Jun-15)	153(Jun-1)
	CV (%)	4	4	5	6
	SD (days)	7	7	8	10
	75 percentiles	192 (Jul-10)	194(Jul-12)	190(Jul-8)	194(Jul-12)
	25 percentiles	185 (Jul-3)	185 (Jul-3)	180(Jun-28)	183(Jul-1)
EOS	Latest (DOY)	307(Nov-2)	274(Sep-30)	279(Oct-5)	311(Nov-7)
	Mean (DOY)	282(Oct-8)	264(Sep-20)	272(Sep-28)	280(Oct-6)
	Median (DOY)	282(Oct-8)	265(Sep-21)	273(Sep-29)	279(Oct-5)
	Earliest (DOY)	248 (Sep-4)	255(sep-11)	257(Sep-13)	255(Sep-11)
	CV (%)	5	3	2	5
	SD (days)	13	8	5	12
	75 percentiles	291(Oct-17)	271(Sep-27)	276(Oct-2)	282(Oct-8)
	25 percentiles	275(Oct-1)	256(Sep-12)	269(Sep-25)	274(Sep-30)
LGS	Longest (Days)	123	89	111	129
	Mean (days)	93	74	86	95
	Median (days)	95	74	86	92
	Shortest (days)	62	61	72	71
	CV (%)	14	12	11	16
	SD (day)	13	9	10	15
	75 percentiles	102	81	95	102
	25 percentiles	87	64	79	84

NB: DOY is day of years, SOS is start date of growing season , EOS is end date of growing season, LGS is length of growing season, CV is coefficient of variation and SD is standard deviation.

Appendix Table 2. Start date, end date and length of successful *Belg* growing season and risk (%) of planting date failure at four stations in the North Eastern Amhara, Ethiopia, 1992-2012.

Parameters	Statistics	Stations			
		Kombolcha	Kobo	Lalibela	Srinka
SOS	Latest (DOY)	90 (Mar-30)	90(Mar-30)	89(Mar-29)	89(Mar-29)
	Mean (DOY)	84 (Mar-24)	81(Mar-21)	81(Mar-21)	79(Mar-19)
	Median (DOY)	87 (Mar-27)	81(Mar-21)	83(Mar-23)	81(Mar-21)
	Earliest (DOY)	70(Mar-10)	70(Mar-10)	71(Mar-11)	62(Mar-2)
	CV (%)	7	10	9	10
	SD (days)	8	8	7	8
	75 percentiles	89(Mar-29)	90(Mar-30)	87(Mar-27)	86(Mar-26)
	25 percentiles	80(Mar-20)	74(Mar-14)	73(Mar-13)	74(Mar-14)
	Risk of failure (%)	43	58	66	33
EOS	Latest (DOY)	152(May-31)	152(May-31)	152(May-31)	156(Jun-4)
	Mean (DOY)	152(May-31)	152(May-31)	152(May-31)	152(May-31)
	Median (DOY)	152(May-31)	152(May-31)	152(May-31)	153(Jun-1)
	Earliest (DOY)	152(May-31)	152(May-31)	152(May-31)	152(May-31)
	CV (%)	0	0	0	2
	SD (days)	0	0	0	3
	75 percentiles	152(May-31)	152(May-31)	152(May-31)	156(Jun-4)
	25 percentiles	152(May-31)	152(May-31)	152(May-31)	152(May-31)
LGS	Longest (Days)	84	84	82	90
	Mean (days)	70	71	71	75
	Median (days)	69	72	69	73
	Shortest (days)	62	62	63	68
	CV (%)	11	12	10	9
	SD (day)	8	9	8	7
	75 percentiles	77	78	79	79
	25 percentiles	63	62	65	70

NB: DOY is day of years, SOS is start date of growing season , EOS is end date of growing season, LGS is length of growing season, CV is coefficient of variation and SD is standard deviation.

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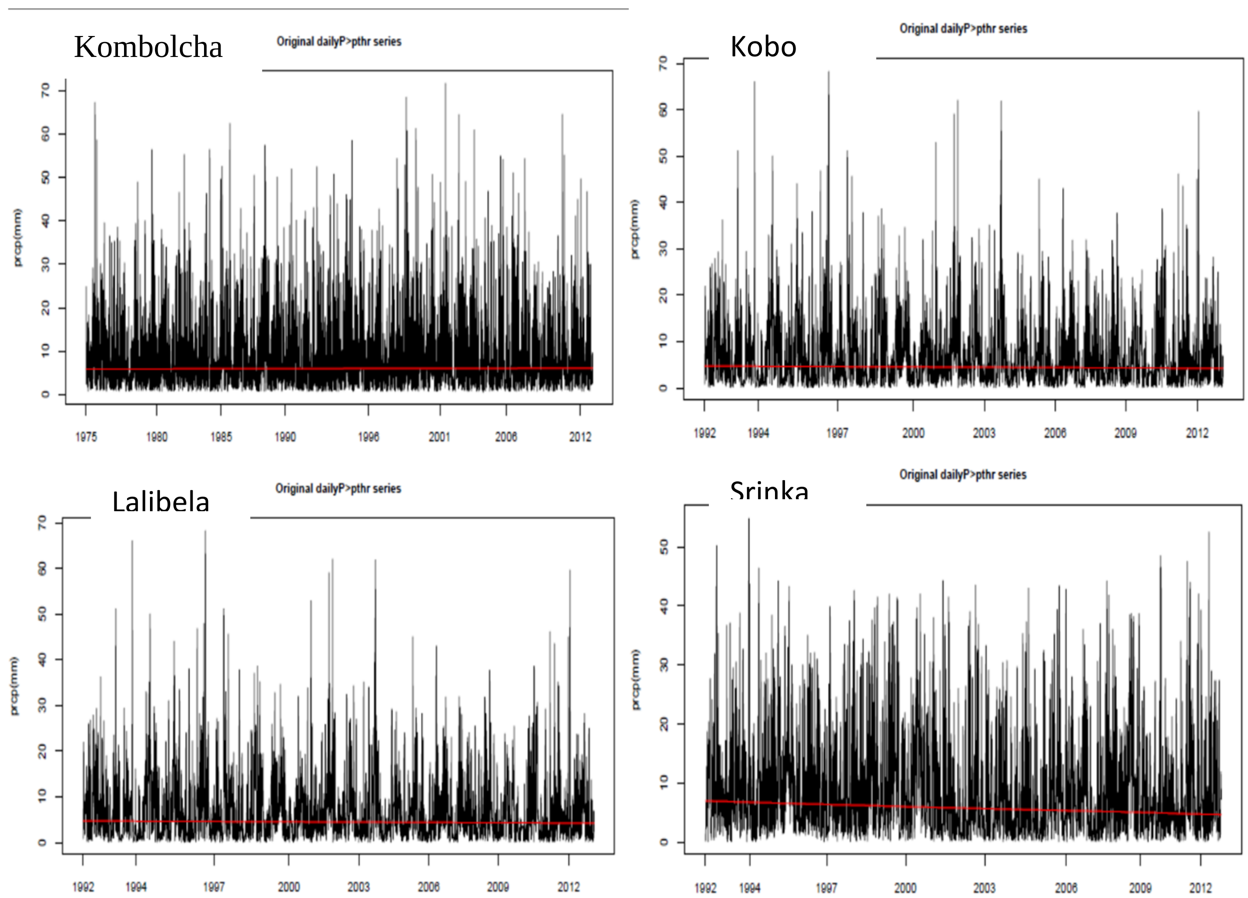
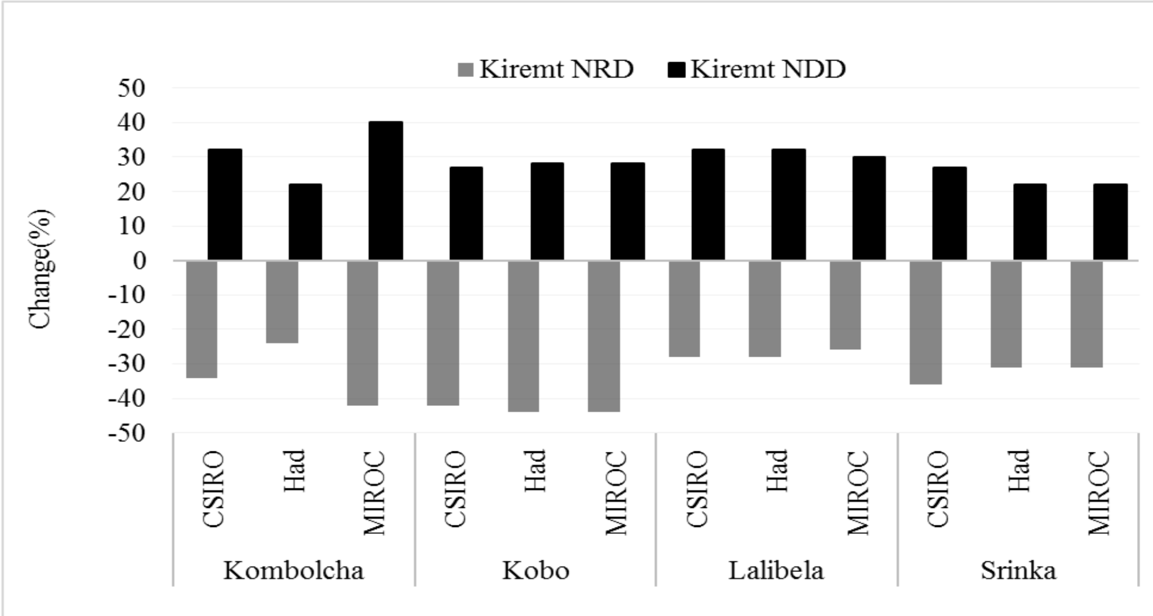
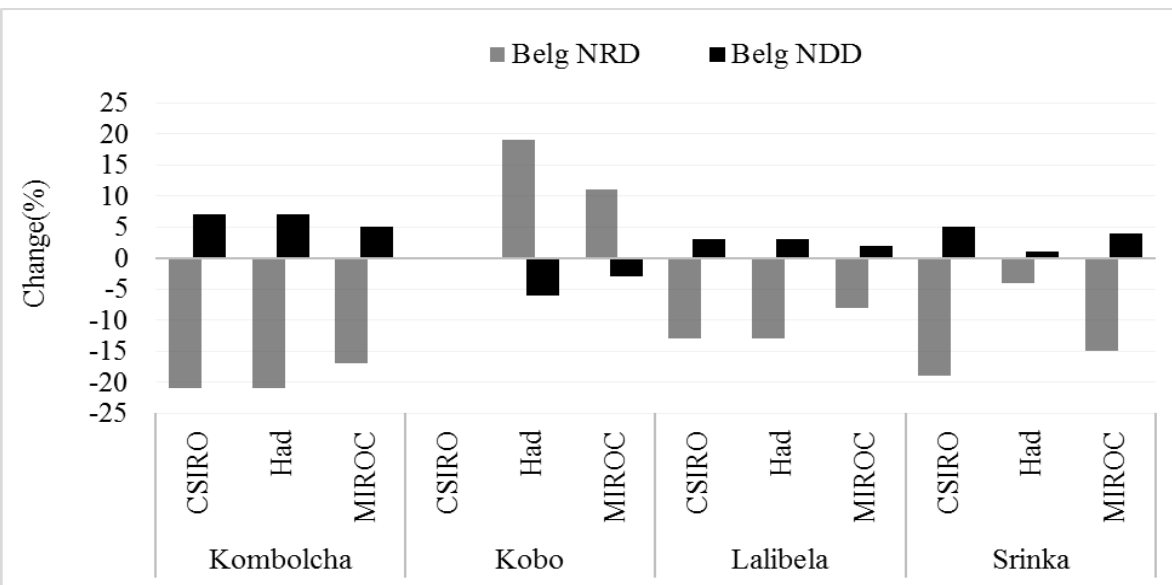


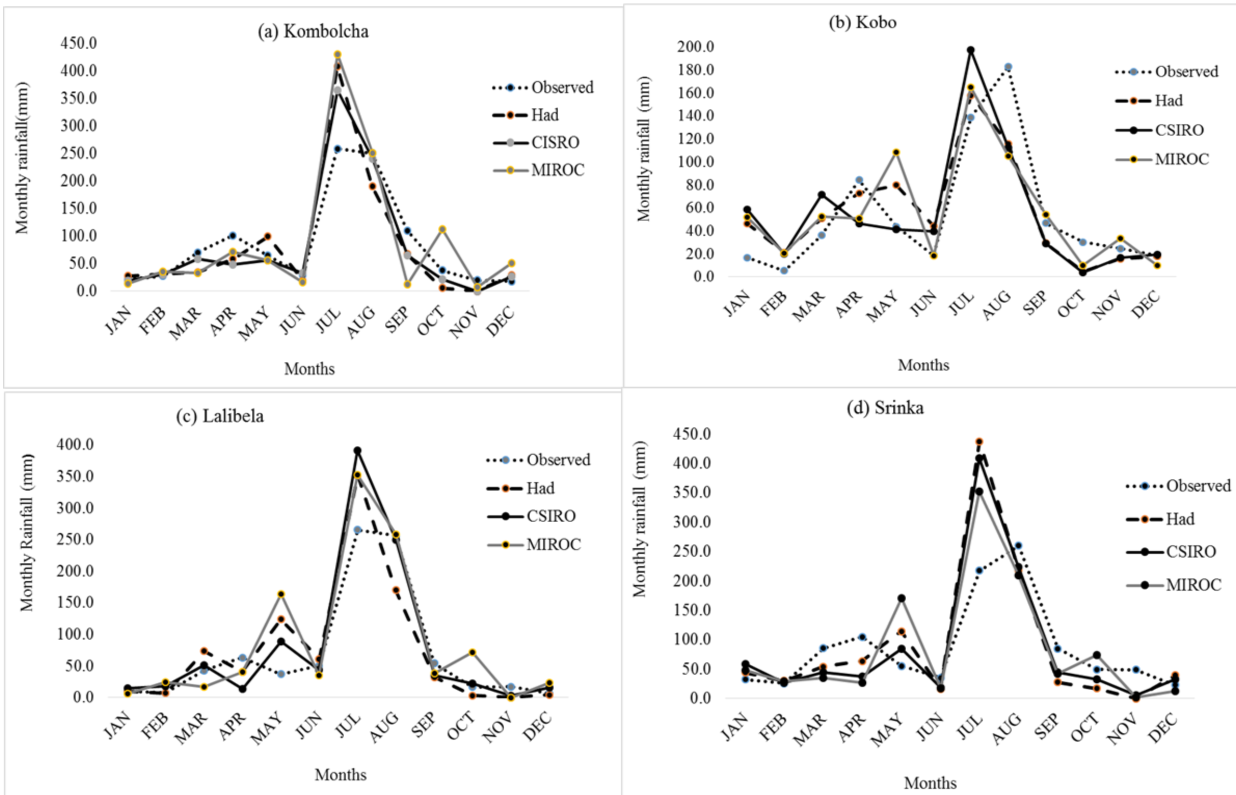
Appendix Figure 1. Daily precipitation pattern series homogeneity test outputs at Kombolcha, Kobo, Lalibela and Srinka stations in the North Eastern Amhara, Ethiopia, during 1992-2012.



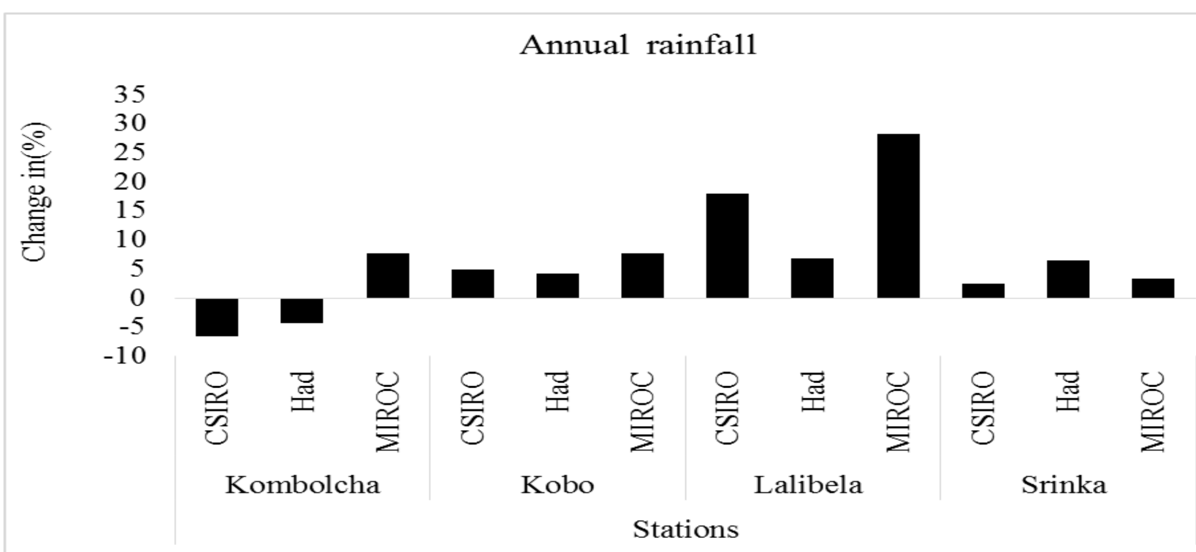
Appendix Figure 2 Changes in seasonal *Kiremt* number of rainy and dry days by 2021-2040 under RCP4.5 emission scenario as predicted by CSIRO, Had and MIROC GCMs compared to base period 1992-2012 at four stations in the North Eastern Amhara, Ethiopia.



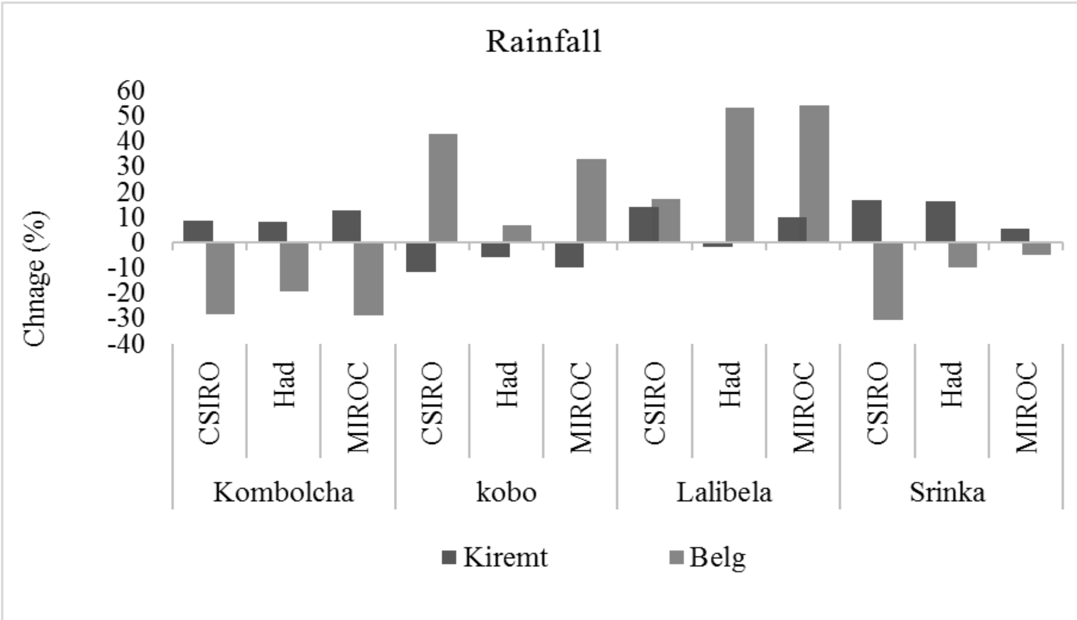
Appendix Figure 3 Changes in seasonal *Belg* number of rainy and dry days by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC GCMs relative to 1992-2012 at four stations in the North Eastern Amhara, Ethiopia



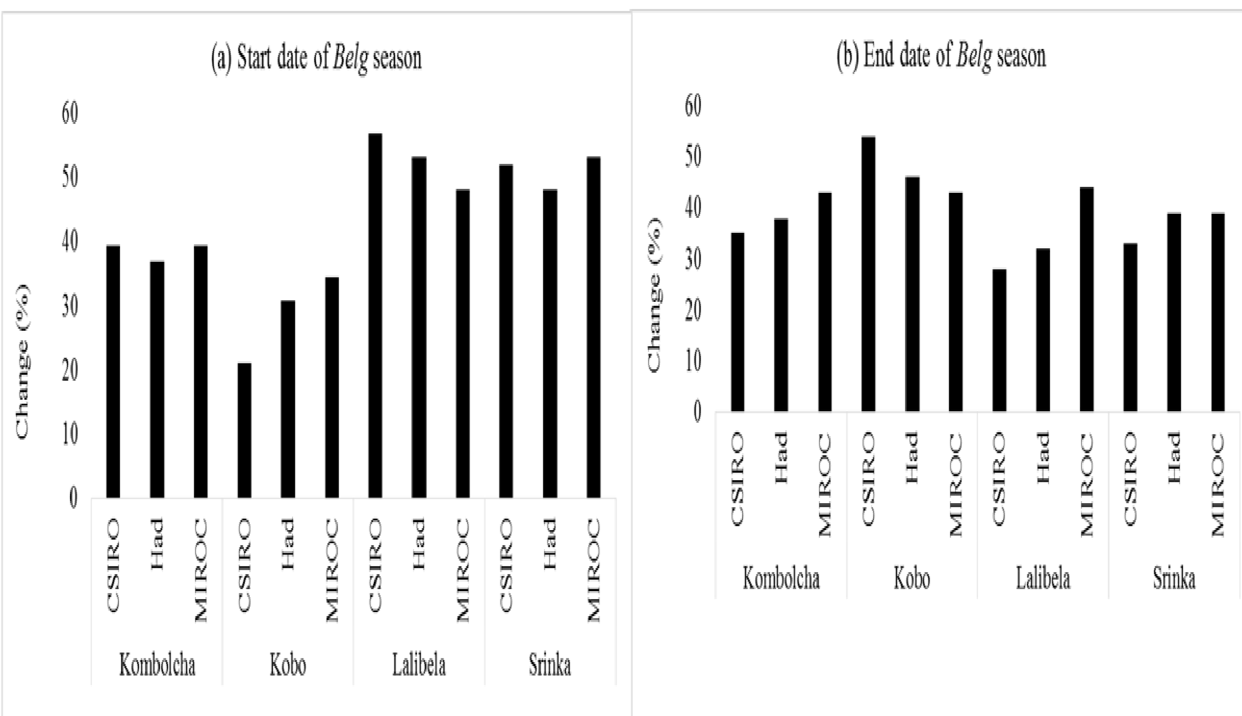
Appendix Figure 4. Future rainfall patterns for 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC models relative to base period (1992-2012) in the North Eastern Amhara, Ethiopia.



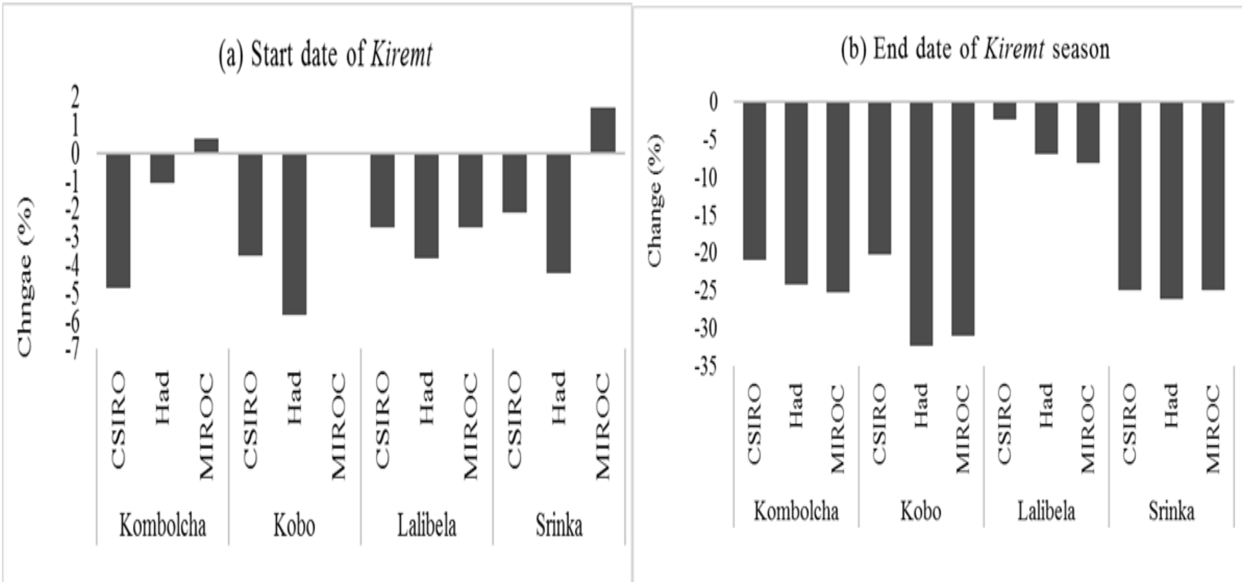
Appendix Figure 5 Changes in annual rainfall totals by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC GCMs relative to 1992-2012 at four stations in the North Eastern Amhara, Ethiopia.



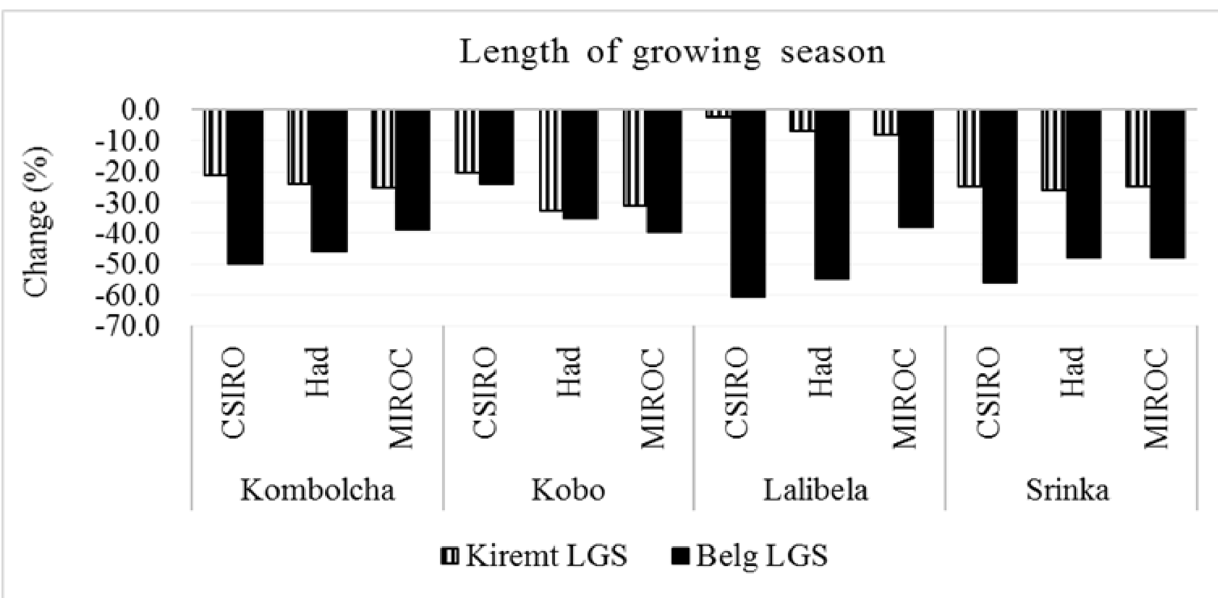
Appendix Figure 6 Changes in seasonal *Kiremt* and *Belg* rainfall totals by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC GCMs compared to base period 1992-2012 at four stations in the North Eastern Amhara, Ethiopia.



Appendix Figure 7 Changes in (a) start and (b) end date of Kiremt growing season by 2021-2040 under RCP4.5 emission scenario by CSIRO, Had and MIROC GCMs relative to 1992-2012 at four stations in the North Eastern Amhara, Ethiopia.



Appendix Figure 8 Changes in (a) start and (b) end date of *Belg* growing season by 2021-2040 under RCP4.5 emission scenario as predicted by different GCMs relative to 1992-2012 at four stations in the North Eastern Amhara, Ethiopia.



Appendix Figure 9 Changes in length of *Kiremt* and *Belg* growing season by 2021-2040 under RCP4.5 emission scenario as predicted by CSIRO, Had and MIROC GCMs relative to 1992-2012 at four stations in the North Eastern Amhara, Ethiopia.