



Spatio-temporal variability and trends of precipitation and extreme rainfall events in Ethiopia in 1980–2010

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Abstract

This article summarizes the results from an analysis conducted to investigate the spatio-temporal variability and trends in the rainfall over Ethiopia over a period of 31 years from 1980 to 2010. The data is mostly observed station data supplemented by bias-corrected AgMERRA climate data. Changes in annual and *Belg* (March–May) and *Kiremt* (June to September) season rainfalls and rainy days have been analysed over the entire Ethiopia. Rainfall is characterized by high temporal variability with coefficient of variation (CV, %) varying from 9 to 30% in the annual, 9 to 69% during the Kiremt season and 15–55% during the Belg season rainfall amounts. Rainfall variability increased disproportionately as the amount of rainfall declined from 700 to 100 mm or less. No significant trend was observed in the annual rainfall amounts over the country, but increasing and decreasing trends were observed in the seasonal rainfall amounts in some areas. A declining trend is also observed in the number of rainy days especially in Oromia, Benishangul-Gumuz and Gambella regions. Trends in seasonal rainfall indicated a general decline in the Belg season and an increase in the Kiremt season rainfall amounts. The increase in rainfall during the main Kiremt season along with the decrease in the number of rainy days leads to an increase in extreme rainfall events over Ethiopia. The trends in the 95th-percentile rainfall events illustrate that the annual extreme rainfall events are increasing over the eastern and south-western parts of Ethiopia covering Oromia and Benishangul-Gumuz regions. During the Belg season, extreme rainfall events are mostly observed over central Ethiopia extending towards the southern part of the country while during the Kiremt season, they are observed over parts of Oromia, (covering Borena, Guji, Bali, west Harerge and east Harerge), Somali, Gambella, southern Tigray and Afar regions. Changes in the intensity of extreme rainfall events are mostly observed over south-eastern parts of Ethiopia extending to the south-west covering Somali and Oromia regions. Similar trends are also observed in the greatest 3-, 5- and 10-day rainfall amounts. Changes in the consecutive dry and wet days showed that consecutive wet days during Belg and Kiremt seasons decreased significantly in many areas in Ethiopia while consecutive dry days increased. The consistency in the trends over large spatial areas confirms the robustness of the trends and serves as a basis for understanding the projected changes in the climate. These results were discussed in relation to their significance to agriculture.

1 Introduction

Agriculture is the main source of livelihood to a wide majority of Ethiopia's population. It employs 80% of the labour force and accounts for 45% of the GDP and 85% of the export revenue (FDRE 1997; CSA 2014) in any single year. Since

much of the agriculture is rain-fed, the productivity of agriculture and the nation's GDP varies in response to the amount and distribution of rainfall during the crop season (Petherick 2012). With less than 2% land under irrigated agriculture, rainfall variability and associated droughts have historically been major causes of food shortages and famine in the country (Wood 1977; RRC 1985; Pankhurst and Johnson 1988; MoWR 2005). It is estimated that a 10% decrease in seasonal rainfall generally translates into 4.4% decrease in the country's food production (von Braun 1991). Ethiopia faces droughts of varying magnitude at regular intervals. Over the past 30 years, the country faced seven severe drought events in 1983–1985, 1988, 2000, 2002–2003, 2006, 2011 and 2015 with the drought during the period 1983–1985 being one of

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the worst that the country has ever faced. It was reported that more than one million people died of starvation during this one event. Though the country has made significant strides with a double digit growth rate over the past decade, it is still vulnerable to droughts and other climatic disturbances. El Niño-induced drought in 2015 affected 4.5 million people in the drought-hit regions of Ethiopia (UNICEF 2015). In addition to these widespread and severe droughts, the country faces several localized events of lower magnitude affecting pockets much more frequently. Given the fact that these natural disturbances will continue to occur, albeit at a higher frequency, under climate change, there is a need to focus on more effective ways to mitigate the negative impacts arising from these shocks and ensure that the communities dependent on climate sensitive sectors such as agriculture are resilient enough to overcome the challenges. One important first step in adapting to current and future climatic conditions is to have a good understanding of the trends in the climatic conditions and their variability over space and time.

Rainfall over Ethiopia exhibits high spatial variability, induced by large variation in the topography which varies from below sea level in the north-east to 4620 m in the west, giving rise to multitude of agro-ecological zones (AEZs). Many researchers have recognized different agro-climatic zones and associated them with the traditional system which identifies five categories based on altitude, rainfall and temperature (Zerihun 1999; MoA 2000). The five traditional zones are Bereha (hot lowlands), kola (moist warm), weinadega (dry warm), dega (cold) and wurch (very cold alpine). Since many of these classifications are not comprehensive, MoA (2000) has adopted the current AEZ classification which is based on the basic ecological elements of climate, physiography, soils, vegetation and farming systems. According to this system, the country is divided into 18 major AEZs and these are named by terms that describe the broad moisture and elevation conditions of the areas. Though climate variability affects the productivity of agricultural systems in all the zones, the water-limited low altitudinal zones such as dry kola and dry weinadega are generally exposed to a high degree of climate risk.

The erratic and unreliable spatial and temporal distribution of rainfall during the crop seasons is the single most important factor determining the national crop production and its year-to-year variability (Deressa et al. 2008). Key variables of rainfall with significant impact on performance of agricultural systems include the onset and cessation of the rainy season, the amount and distribution of rainfall, the length and frequency of occurrence of dry and wet spells and extreme rainfall events. Previous studies to understand climate variability are mostly based on area average rainfall data for north central highlands of Ethiopia (Osman and Sauerborn 2002; Seleshi and Demaree 1995) which indicated that the second half of the twentieth century suffered predominantly negative rainfall anomalies. Seleshi and Zanke (2004) studied rainfall

variability over Ethiopia and illustrated that there is no significant trend in rainfall amounts and rainy days. Studies on the occurrence of extreme events over Ethiopia indicate a declining trend in the frequency of heavy rains (Easterling et al. 2000, Endalew 2007) and an increasing trend in the frequency of dry extremes along with an increase in the number of warm days and nights (McSweeney et al. 2010). In a study by Aklilu et al. (2013), with climate data for 11 stations from 3 major eco-environments, positive trends were observed for the maximum temperature, warm days, warm nights and temperature extremes but no significant trend was noted in the case of precipitation extremes at any of the stations studied. Most of these studies are limited in their assessment to specific regions and seasons in the country, and a complete assessment of trends and changes in rainfall and its variability including extreme events covering the entire country and all the seasons is missing.

This study aims to fill this gap by conducting a more comprehensive assessment of the variability and trends in the annual and seasonal rainfall amounts and precipitation extremes using three decades of station data with stations distributed all over Ethiopia. Such climate information has shown potential for use in developing strategic adaptation and mitigation measures aimed at improving the resilience of agricultural systems to climate shocks. Hence, the main objective of this study is to provide (1) a comprehensive assessment of variability in annual and seasonal rainfall amounts over Ethiopia, (2) an assessment of trends in seasonal/annual rainfall amounts and their distribution and (3) an analysis of the magnitude and frequency of occurrence of extreme precipitation events.

2 Materials and methods

This study is focused on the eight regions of Ethiopia which are second-level administrative sub-divisions. The rainfall and temperature data sets used in the current study are part of the proprietary archives of the Ethiopian National Meteorological Agency (NMA) and Ethiopian Institute for Agricultural Research (EIAR). In this analysis, we used all the available station data after thorough quality checks. Since trends at individual weather stations reflect both long-term trends and the influences of local changes such as land use and land cover, we supplemented the station data with bias-corrected AgMERRA (Rienecker et al. 2011) data to achieve better spatial representation and enhance the credibility of the trends.

2.1 Data collection and quality control

Initially, efforts were made to generate standard metadata about all of the available daily meteorological data (rainfall, maximum and minimum temperatures) that describes all

entries with name of the station; latitude, longitude and altitude of the location; climatic variables for which data is available and start and end years in the record. The metadata included more than 900 stations around the country for which the required data is available. Using the metadata information, we have selected 120 stations for which 30 or more years' rainfall and maximum and minimum temperature data are available. From this, 99 stations were finally selected as suitable for trend and variability analysis based on the length of continuous record (at least 30 years) and less than 10% missing data. However, the spatial coverage of the stations is not uniform with many stations located over the highlands of central Ethiopia leaving lowland areas underrepresented. A positive aspect of this skewed distribution is that most of the stations are located over the regions where the spatial variability of rainfall is the highest. Station distribution over the lowland areas is extremely sparse with no stations along the border with Somali in the east and with Kenya in the south and along the border with South Sudan and Sudan in the north-west. In order to generate homogeneous time series data over Ethiopia at a spatial resolution of 50×50 km and to fill the gaps in the observed data, we used the bias-corrected AgMERRA (Rienecker et al. 2011) climate forcing data sets created for the Agricultural Model Inter-comparison and Improvement Project (AgMIP). Daily meteorological data (rainfall, maximum and minimum temperatures) for the period 1980–2010 were developed from the closest AgMERRA grid data after bias correction with the station data. Finally, a data set with 374 station/point data that are uniformly distributed across the country was developed and used in this study. As most stations have continuous data with little or no missing data for the period 1980 to 2010, this period was used to investigate the trends in rainfall and associated variables. Efforts were made to extend the time series of rainfall data; however, due to civil conflict during 1970 and 1980s, data for most stations during this period is either missing or incomplete with gaps for extended periods.

In addition to the routine quality checks that NMA and EIAR perform on data in their archives, extensive evaluations were performed on the entire data set to determine data completeness and quality. These quality checks were performed using R-Climdex (Zhang and Yang 2004) which flagged out the spurious values. Potential outliers were identified using interquartile range (IQR). The IQR uses the median and the lower and upper quartiles (25th and 75th percentiles) to create fences required to identify extreme values in the tails of distribution. The lower fence of quartile $1 - 1.5 \times (IQR)$ and the upper fence of quartile $3 + 1.5 \times (IQR)$ were used to identify the outliers in the data. The IQR is the length of the box in a box-and-whisker plot. Missing values and negative rainfall events were replaced with AgMERRA data. Suspected outliers in rainfall were also identified by visual scrutiny of monthly and daily plots.

2.2 Analysis methods

Using the daily rainfall data, monthly and seasonal averages were derived. Though there are three seasons in Ethiopia, this analysis is limited to *Kiremt* or *Meher* season (summer) from June to August which accounts for 74% of the annual rainfall and to *Belg* season (spring) from March to May which accounts for 25% of the annual rainfall. The third season is the dry and cool season, running from October to January, locally known as *Bega* season, and rainfall is limited to a small area bordering Kenya. While rainfall during Kiremt season is more widespread covering the entire country, rainfall during Belg season is limited to the south and south-west regions. To characterize the spatial variability of rainfall at the zonal scale, area-weighted rainfall was computed. A summary of the descriptive statistics such as mean, standard deviation and coefficient of variation (CV, %) for annual and seasonal rainfall amounts for the eight regions is presented in Table 1.

2.3 Trend analysis methods

Two non-parametric methods (Mann–Kendall and Sen's slope estimator) were used to detect the significant temporal trends in the meteorological variables. The Mann–Kendall test is a non-parametric test, which does not require the data to be distributed normally. The second advantage of the test is its low sensitivity to abrupt breaks due to inhomogeneous time series (Jaagus 2006). The Mann–Kendall test statistic S (Kendall 1975), which measures the trend in the data, is defined as the sum of the number of positive differences minus the number of negative differences between consecutive sample results. The standard normal variable Z is used to identify the direction of the trend and its significance. Positive Z values indicate increasing trend while negative values display decreasing trend. When testing the trends for significance at the α significance level, the null hypothesis was rejected for an absolute value of Z greater than $Z_{1-\alpha/2}$, obtained from the standard normal cumulative distribution tables (Partal and Kahya 2006; Modarres and Silva 2007). In this study, significance levels of $\alpha = 0.05$ were applied. Sen's slope is used to identify linear trend; if it is present in a time series, then the true slope (change per unit time) was estimated by using a simple non-parametric procedure developed by Sen (1968).

2.4 STARDEX indices

Spatial and temporal changes in the number and amount of extreme rainfall events were characterized using a set of indices developed by STARDEX (Statistical and Regional Dynamical Downscaling of Extremes for European region) (Stardex 2002). STARDEX version 3.3.0 is arrayed to compute 52 indices for quantifying temporal changes in the extreme weather events during 1980–2010. The daily weather

Table 1 Mean and variability in rainfall in different regions (second-level administrative division) of Ethiopia derived from the station data

Region	Altitude range (m)	Annual rainfall (mm)			MAM rainfall (mm)			JJAS rainfall (mm)		
		Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)
Afar	– 116 to 1600	740.5	182.3	25.0	150.2	75.5	50.00	439.9	128.4	30.0
Amhara	500 to 4620	1582.6	195.2	12.4	189.0	74.0	39.5	981.4	145.2	15.2
Benishangul-Gumuz	550 to 2500	2281.5	301.8	13.0	235.4	75.0	31.8	1415.6	206.7	14.4
Gambela	450 to 2000	1796.9	259.6	14.4	394.5	89.1	23.0	842.7	132.1	15.8
Oromia	1500 to 2300	1638.4	199.0	12.5	342.9	98.8	30.0	849.4	113.6	15.4
SNNPR	500 to 2000	1581.3	176.2	11.3	461.1	88.4	19.6	646.8	82.2	13.4
Somali	350 to 1230	395.3	138.6	40.0	225.6	76.8	34.1	106.9	60.3	60.0
Tigray	500 to 1500	1038.5	174.3	17.1	122.8	60.2	49.2	649.4	133.7	21.2

data for precipitation was used to compute the selected indices in the current climate. The selection of indices to describe extreme events is based on several characteristics that included relevance to crop production, ease of interpretation and relevance to planning and decision-making. The indices also covered both frequency and intensity. Six indices of extreme rainfall were calculated for each year in the period, and these include the number of events above the average long-term 95th percentile; the greatest 3-, 5- and 10-day rainfall events and the maximum consecutive dry and wet spells. In order to understand the changes in extreme event frequency, the Haylock and Nicholls (2000) approach was used. This approach uses the mean 95th percentile value which varies from one point to the other and is well-suited to account for high spatial variability compared to a fixed threshold for the entire study area. The extreme index is computed by counting the number of events in a given year above the mean of 95th percentile which varied from 17 to 128 mm across the country. Daily precipitation greater than or equal to 1.0 mm was considered as a rainy day as per the NMA definition of a rainy day.

3 Results

3.1 Spatial patterns of rainfall over Ethiopia

Rainfall amounts for the period 1980–2010 displayed high spatial variability which is largely associated with the altitudinal variation within the country. The high-altitude regions received more rainfall than the low-altitude regions where the climate is mostly semi-arid to arid. In the highland areas of central and north-west regions, annual rainfall varied from 1200 to 2700 mm while that in the lowland areas in the eastern part of the country varied from 500 to 700 mm. The length of the rainy season also showed considerable spatial variation. In the highlands, the duration of the rainy season increased from the north to the south (Fig. 1). The season is limited to

3 months from July to September in Tigray region in the north while that in the south in Southern Nations, Nationalities, and Peoples' Region (SNNPR) extends to 8 months from March to October. To the east of these highland areas, in the rift valley zone of Oromia region, rainfall is bimodal with peaks in March–April and August–October. The bimodal distribution continues in the eastern lowland regions of Somalia and Afar with reduced amount of rainfall during the two seasons.

Though nearly 80% of the southern and south-eastern parts of Ethiopia receive rainfall during March–May (MAM) (spring) Belg season, good rainfall of 400 mm or more is limited to parts of SNNPR and Oromia regions (Fig. 2). Rainfall during this period over much of the central highlands and rift valley regions is low and varies between 200 and 400 mm while the north and eastern parts of the country remain relatively dry with less than 200 mm. Rainfall during the main June–September (summer) Kiremt season is more widespread and covers the entire country with a steep gradient from north-west to south-east where the average rainfall declines to as low as 170 mm. During this period, the highland areas in the central and north-western parts of the country receive 800 mm or more rainfall while the eastern part of the country covering Somali and Afar regions receives less than 400-mm rainfall. Rainfall in the remaining parts of the country, i.e. the region between western high rainfall and eastern low rainfall areas, from parts of Tigray in the north to SNNPR in the south ranges between 400- and 800mm rainfall.

3.2 Temporal variability in the annual and seasonal rainfalls

The temporal variability in the annual and seasonal rainfalls was assessed using coefficient of variation (CV, %) which showed a strong relationship with the amount of rainfall received during that period (Fig. 3). The CV for annual rainfall varied from 9 to 30%, Kiremt season rainfall varied from 9 to 69% and the Belg season rainfall varied between 15 and 55% (Fig. 4). The variability in the annual rainfall is less than 12%

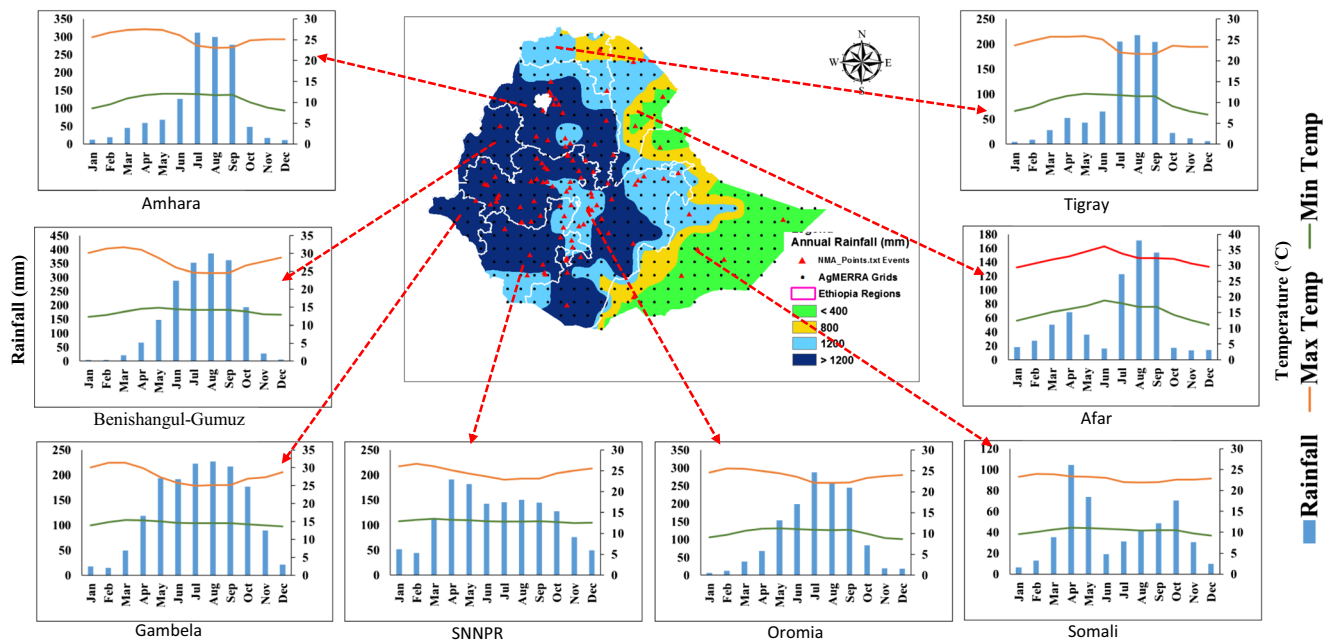


Fig. 1 Spatial distribution of annual rainfall (mm) with AgMERRA grid points and station locations. Black dots represent AgMERRA grid points, and white triangles represent NMA stations. The graphs indicate the

distribution of monthly average rainfall (mm) and maximum and minimum temperatures (°C) for the period 1980–2010 over eight regions of Ethiopia

in the central highland areas while the same exceeds 20% in the lowland areas of Somali and Afar regions. During the main Kiremt season, CV increased in all directions from less than 12% in the central highland areas. The highest increase is towards the east, where CV values in excess of 50% are common in many parts of Somali and Afar regions. During the Belg season, CV is greater than 30% in most areas, but this is not a crop season in many of these areas. In the south–south-

west region, where rainfall during this period is more than 400 mm, CV varied between 16 and 30%. In general, annual and seasonal rainfalls are highly variable over Somali and Afar regions which receive relatively low rainfall. Among the high-rainfall areas, highlands of central Ethiopia exhibited low variability compared to Gambella and Benishangul-Gumuz where annual rainfall varied from 900 to 2300 mm/year with a CV of 15–20%.

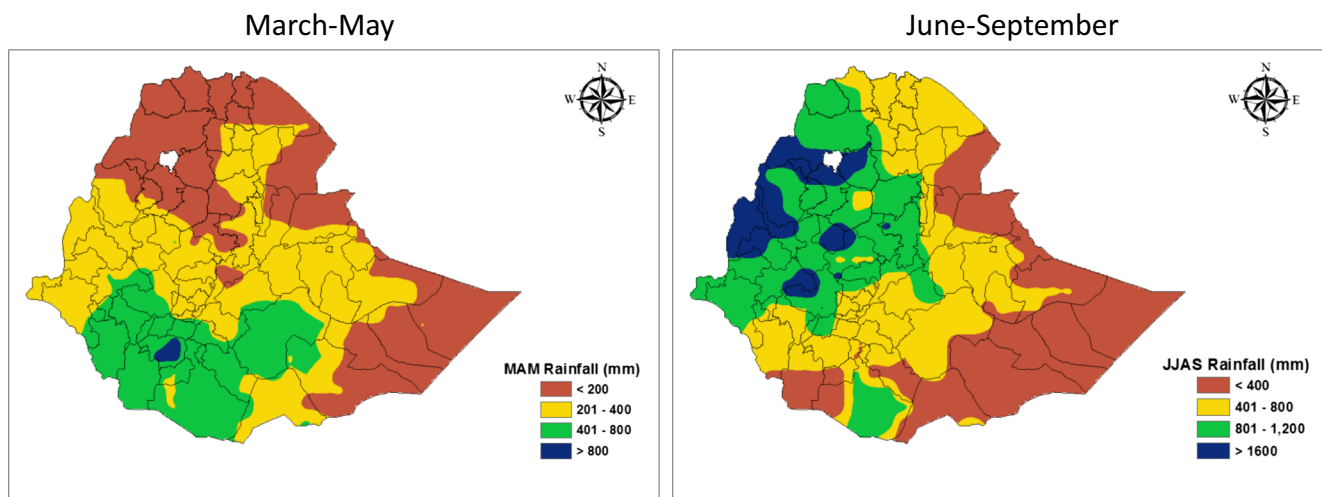
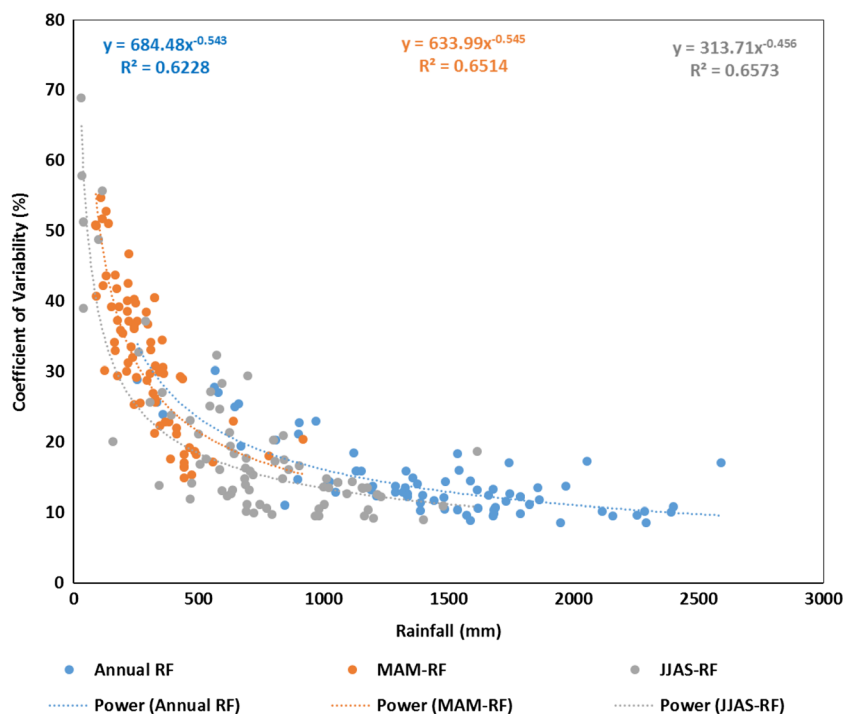


Fig. 2 Spatial distribution of the Belg (left) and Kiremt (right) seasonal mean rainfalls generated by Kriging using 374 grid-point data for the period 1980–2010

Fig. 3 Relationship between annual, March–May *Belg* season and June–September *Kiremt* season rainfall amounts (mm) and coefficient of variation (CV) (%)



3.3 Trends in the annual and seasonal rainfall amounts

The long-term trends in the annual and seasonal rainfall amounts were assessed for all the regions by applying linear regression and Mann–Kendall statistical tests at 5% significance level. The results from the analysis indicated a general non-significant increasing trend in the annual rainfall amounts in all the regions of Ethiopia except for Afar region where the trend is negative. However, a general declining trend was observed in the number of rainy days in all the regions of Ethiopia but the trends are significant only in Afar, Benishangul-Gumuz and SNNPR regions as displayed in Fig. 5. The number of rainy days declined by 30 days in Benishangul-Gumuz, by 26 days in SNNPR and by 13 days in Afar between the periods 1980 and 2010.

Significant increasing or decreasing trends were also observed in the Belg and Kiremt seasonal rainfall amounts in some of the regions. The Mann–Kendall test for Belg season (MAM) showed significant decline in the amount of rainfall along the rift valley covering parts of Amhara, Oromia and SNNPR regions (Fig. 6). This is also the region where Belg season rainfall makes a significant contribution to the total annual rainfall. A decline of 50–150 mm over a period of 31 years is recorded in these areas. No major trend was observed in the rainfall during June to September Kiremt season which contributes more than 70% of the annual rainfall in most regions of the country except for an increasing trend in the Afar and Somali regions. The magnitude of this increase is in the range of 35–55 mm over the past three decades.

3.4 Extreme rainfall events

The general trends of increasing rainfall and decreasing rainy days observed in many regions lead to altering rainfall intensity by increasing the per-event rainfall amount and the frequency of occurrence of extreme events. Figure 7a–f presents the temporal variability in the six indices selected to characterize the trends in extreme events. These indices are calculated for each station and averaged to compute the index at the national level. The results indicated mixed trends. At the national level, a significant increasing trend is noted in the 95th percentile and the greatest 3-, 5- and 10-day rainfall amounts. Further, the anomalies of these indices indicate that much of this change has occurred during the last decade starting from the year 2000. The 95th-percentile rainfall increased from 43.3 mm during 1980–1989 to 64.8 mm during 2001–2010, which is about 50% increase between the first and the last decades in the data. Similarly, the greatest 3-day rainfall increased by 39 mm from 127 mm, 5-day rainfall increased by 40 mm from 151 mm and 10-day rainfall increased by 38 mm from 199 mm between 1980 and 1989 and between 2001 and 2010. However, a declining trend was observed in the maximum number of consecutive wet days which declined to 5.55 from 6.69, a 17% decrease over the 31-year period while no significant change is observed in the maximum number of consecutive dry days.

The increase in the 95th-percentile annual and seasonal rainfall amounts over most parts of the country was subjected to further analysis to identify the areas within the country where these changes are taking place. The change is assessed

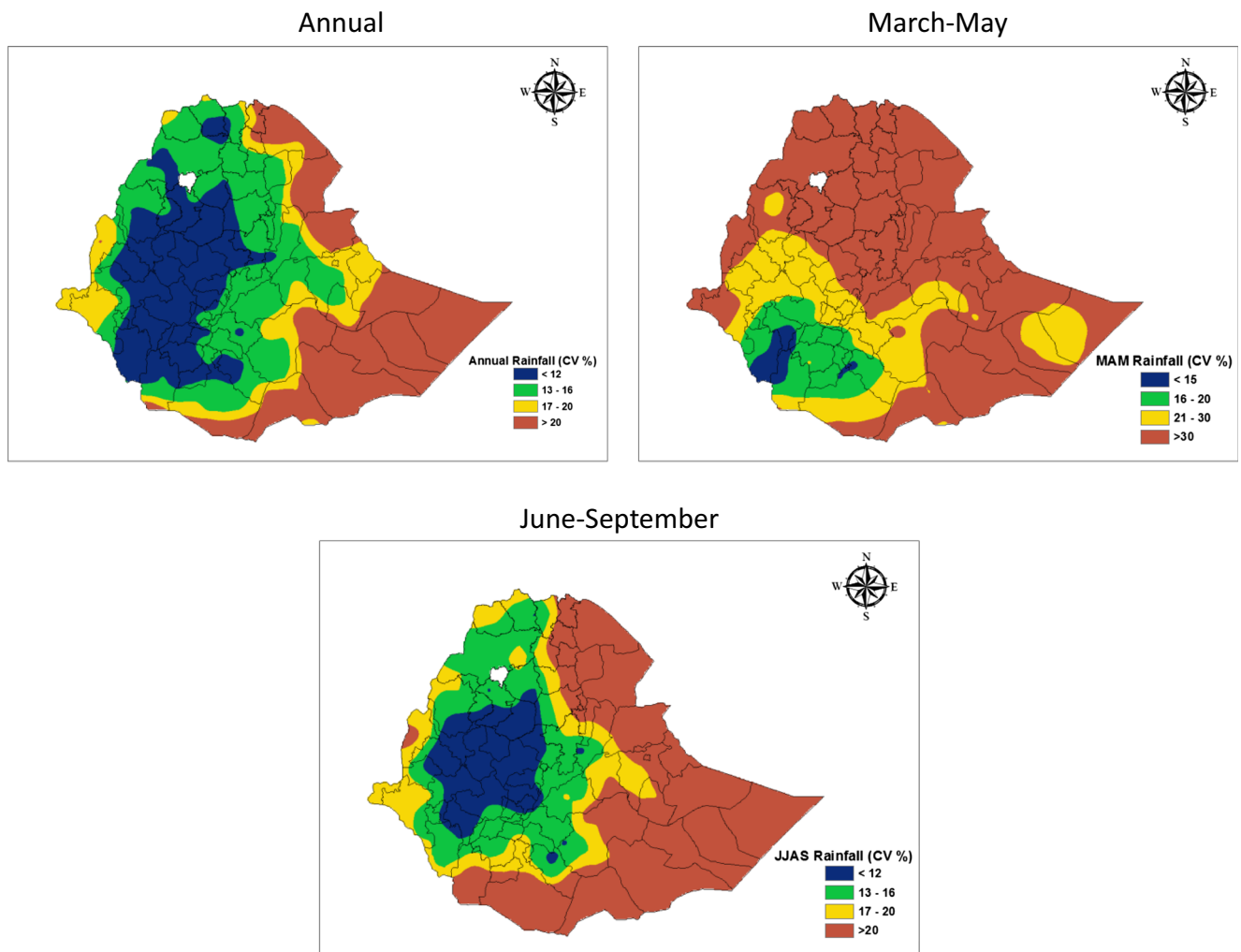


Fig. 4 Spatial distribution of coefficient of variation (CV %) in annual and seasonal rainfalls during the last three decades (1980–2010)

at the station/grid level as percent increase or decrease in the average 95th-percentile rainfall amount between the first and the last 10-year period of the total 31-year period covered by this analysis. The highest increase of more than 50% is observed in most parts of the country except in the rift valley region (Fig. 8). Much of this occurred during the main rainy season from June to September during which > 50% change is recorded in almost all parts of the country except a small area in the south bordering Kenya. In the case of March–May Belg season, the increase in extreme rainfall is high in the western part of the country. An increase is also noted in the frequency of occurrence of extreme rainfall events, events exceeding 95th-percentile rainfall in a year, especially over the eastern and south-western parts of Ethiopia. Central highlands of Ethiopia with an average frequency of six to nine events per year recorded a lower number of extreme events annually compared to other parts of Ethiopia where frequency of extreme events varied between 10 and 15 events during the period from 1980 to 2010. During March to May Belg season,

these events are mostly observed over central Ethiopia extending towards to southern part of the country with a frequency varying from 14 to 16 days. During June–September Kiremt season, extreme rainfall events are spatially observed over parts of Oromia (covering Borena, Guji, Bali, west Harerge and east Harerge), Somali, Gambella, Southern Tigray and Afar regions.

Similar patterns were also observed in the greatest 3-, 5- and 10-day rainfall amounts, and further analysis revealed that the extreme rainfall events are mostly observed over the central part of Ethiopia extending from the west to the east with the highest rainfall of more than 300 mm in west Harerge. These patterns are also observed over the seasons (Table 2). Though a general increase in 3-, 5- and 10-day rainfall intensities is observed in more than 70% of the grids, the number of grid points where the change met 5% significance level ranged between 2 and 20%. Among the indices, consecutive wet days showed a declining trend and consecutive dry days showed an increasing trend in more than 50% of the grids. The percent

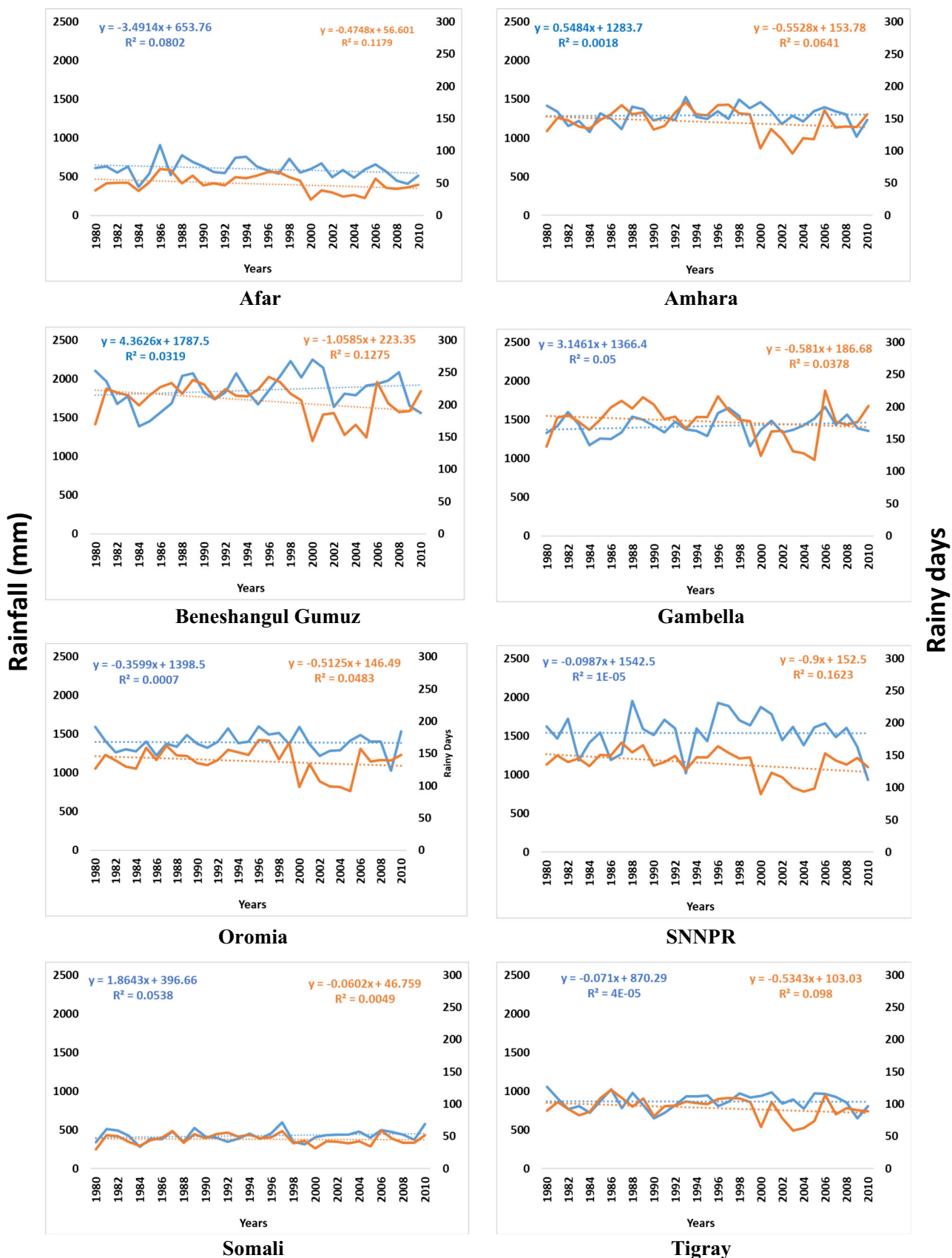


Fig. 5 Trends in long-term annual rainfall (blue dashed line) and rainy days (orange dashed line) over Ethiopia

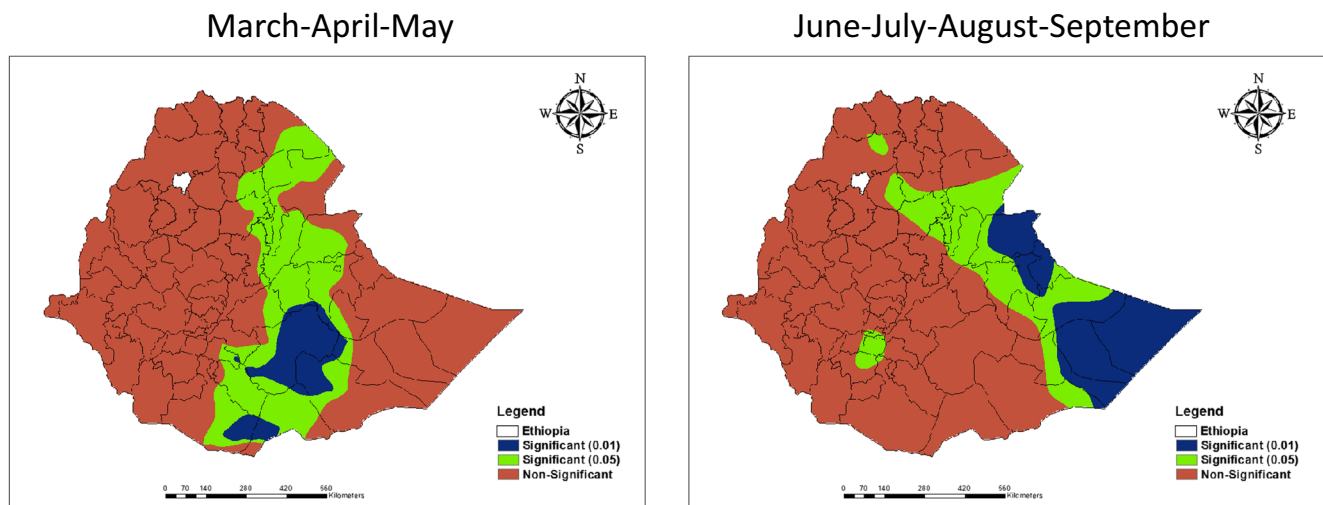


Fig. 6 Trend in March–May and June–September period rainfalls based on the Mann–Kendall statistic over the 1980–2010 period. Zones with significant trend are in green ($p = 0.05$) and blue ($p = 0.01$) colours while red-coloured polygons represent non-significant trends

grids in which the decline in consecutive wet days is significant varied between 25 and 35% in the annual and seasonal time periods. The increase in consecutive dry days is significant in 8 to 24% of the grids.

4 Discussion

4.1 Precipitation trends over the last three decades

It is well-documented that Ethiopia experiences significant temporal and spatial variabilities in the amount and distribution of rainfall across the country. Though the country receives rainfall in three seasons, the main rainy season in most parts of the country is June–September which is locally known as Kiremt season followed by a short rainy season during March–May which is locally referred to as Belg season. The third season, October–December, is important over a small area in the south bordering Kenya. The annual and seasonal rainfall amounts exhibit significant temporal variability which increases with decreasing rainfall amounts as indicated by higher CV in the drier Somali and Afar regions compared to other regions such as Amhara and Benishangul-Gumuz. This analysis made a detailed assessment of the trends in the temporal variability and how they corroborate with the projected long-term changes in the climate from global warming.

The results indicated no major change in the amount of rainfall received annually throughout the country. However, some trends were observed in the Belg and Kiremt seasonal rainfall amounts. Most parts of the country have recorded a reduction in the amount of rainfall received during Belg season. Evidences of declining trends in MAM rainfall in Eastern Africa in general and in Ethiopia in particular were reported by IPCC (2014), Seleshi and Camberlin (2006), Conway et al. (2007), Williams and Funk (2011), Jury and Funk (2012) and

Viste et al. (2012). The impacts of rainfall during this period vary from one country to the other in the region. In Ethiopia, Belg season rainfall is extremely important for the performance of agricultural and pastoral systems, which account for 15–20% of the national food production. In addition, rainfall during the Belg season will also impact the performance of crops during Kiremt season by influencing the soil moisture availability and time of planting. Good Belg season rainfall leads to greater moisture availability and facilitates early planting of long-duration varieties of the main food crops such as maize and sorghum which are high-yielding. Hence, decreasing trends of Belg season rainfall over central Ethiopia will have a significant impact on the production and productivity of agricultural systems in both Belg and Kiremt seasons.

In the case of Kiremt season rainfall, no major trends were observed in the main agricultural zones of the country but a significant increasing trend was observed in the south-eastern parts of Ethiopia mostly covering Somali region. These are traditionally pastoral areas with limited agriculture. However, these positive trends have the potential to make significant contribution to increase the biomass production for livestock and also support the current transition from pastoral to agro-pastoral systems in this region. Another significant finding is the significant decline in rainy days especially in parts of Oromia, Benishangul-Gumuz and Gambella regions. Given the minimal changes in the amount of rainfall in these areas, a decline in the number of rainy days makes rainfall more variable and intense which needs to be considered while planning farm operations and enterprise section in these areas.

The observed trends in rainfall and rainy days are expected to have a significant impact on agriculture in the midlands of the rift valley region where rainfall is the major limiting factor for crop production and farmers are struggling to cope with the current variability. The increasing trend in the rainfall variability and the decreasing trend in the amount of rainfall

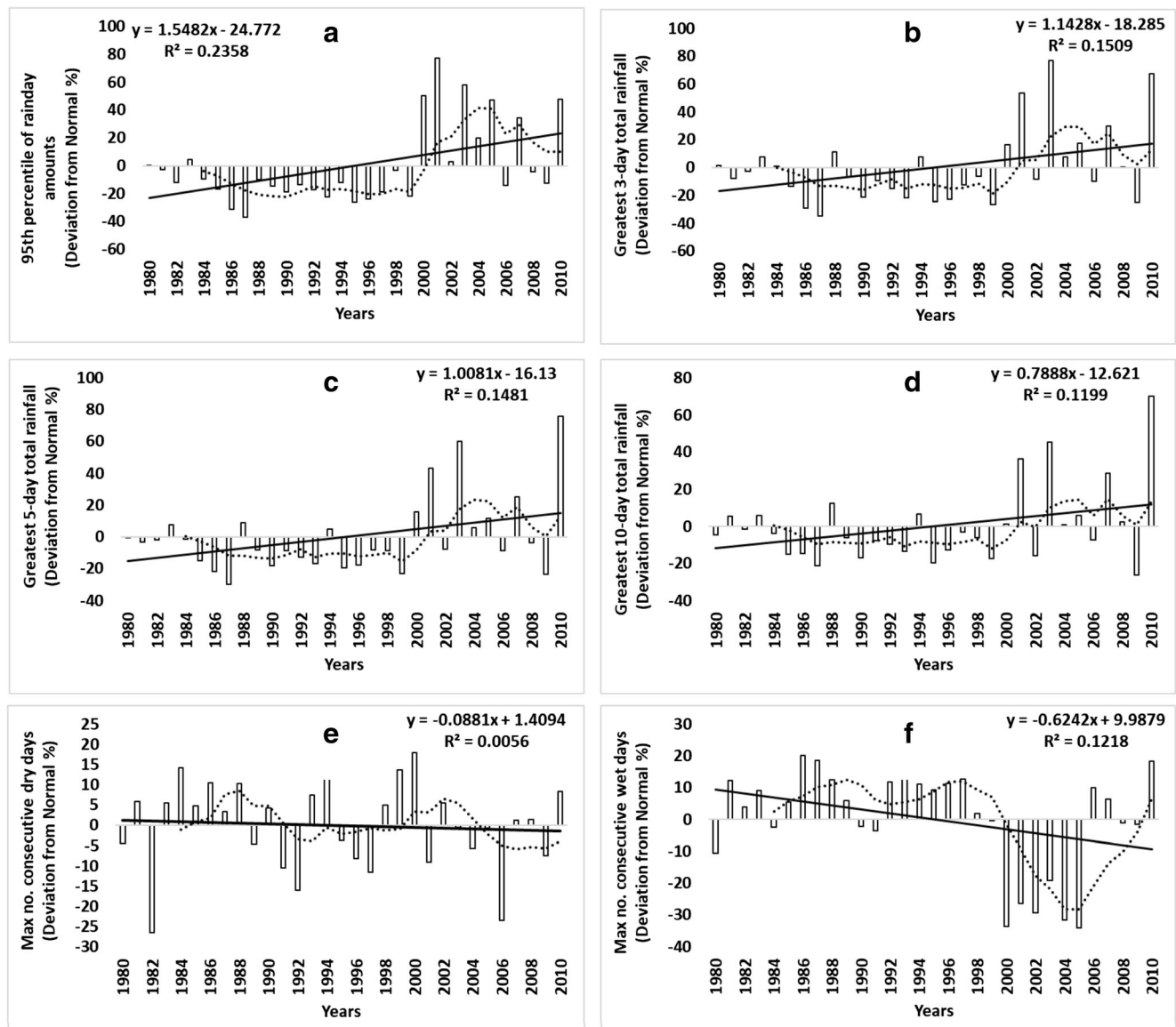


Fig. 7 Trends in the national average extreme precipitation. The solid line represents linear trends in average precipitation indices for the period 1980–2010, and the dotted line represents 5-year moving average. The indices are **a** the 95th percentile of rainy day amounts (pq95), **b** the

greatest 3-day total rainfall (px3d), **c** the greatest 5-day total rainfall (px5d), **d** the greatest 10-day total rainfall (px10d), **e** the maximum number of consecutive dry days (pxcdd) and **f** the maximum number of consecutive wet days (pxcwd)

received during the Belg season are the two trends with a high potential for adverse impacts on the performance of agricultural systems in these areas and which make future agriculture in these areas more challenging.

4.2 Extreme precipitation trends

The general increasing trend in the June–September season rainfall with corresponding decline in the number of rainy days has led to a significant increase in the rainfall intensities and in the occurrence of extreme events. Extreme precipitation indices particularly the intensity indices of 95th-percentile rainy day amounts (mm/day) and the greatest 3-, 5- and 10-

day total rainfall were found to be significantly increasing especially from the year 2000 onwards. Though the increase in most of these indices is observed in more than 70% of the total 374 grid points used in this analysis, the number of grids where the increase is significant at 5% level is low. However, with due attention to the spatial scale at which these changes are occurring covering most parts of the country and also to the fact that much of this has occurred in recent years, we do consider them as robust indicators of the changes occurring in the climatic conditions of Ethiopia. Many past studies on extreme events have reported inconsistent patterns (Seleshi and Camberlin 2006; Bewket and Conway 2007; Rosell and Holmer 2007; Kebede and Bewket 2009; Shang et al. 2010;

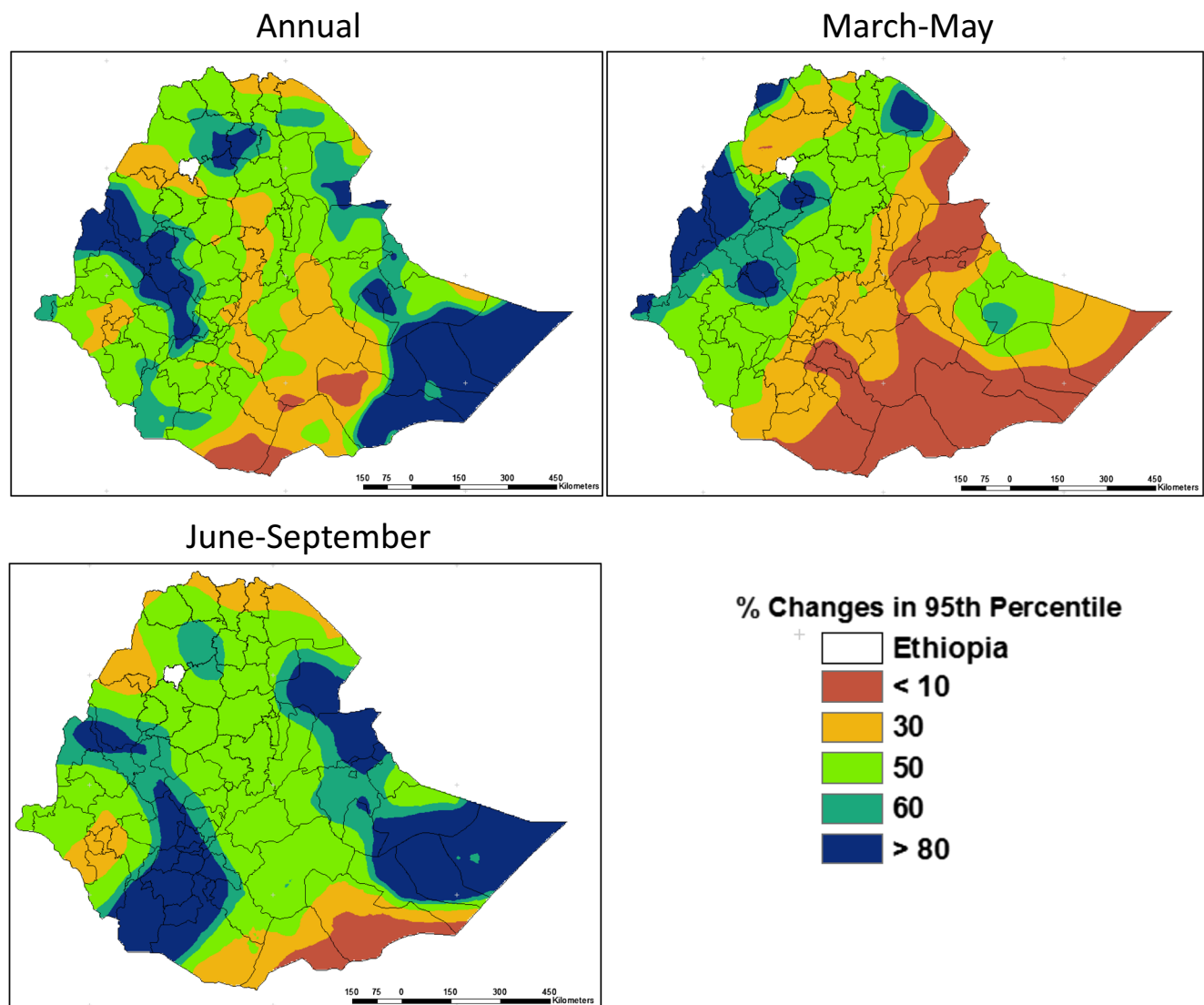


Fig. 8 Percent changes in the 95th-percentile rainfall amounts during 1980–1989 to 2001–2010

Ayalew et al. 2012). However, there is a growing evidence that the variability and also the frequency of occurrence of extreme events are increasing over the past two decades (IPCC 2014; Fischer and Knutti 2015; Herring et al. 2015).

Reduction in the rainy days also affected the length and duration of the dry and wet spells. While the maximum number of consecutive dry days increased and the consecutive wet days declined in the annual and seasonal time steps with the highest being in the MAM season, significant changes were noted in the eastern-central parts extending to southern Ethiopia covering parts of Amahara, Oromia and SNNP regions. Approximately 15 to 20% of the stations in the southern, south-western and south-eastern parts of Ethiopia displayed decreasing patterns in Belg season rainfall (Funk et al. 2005). Complex patterns in increasing and decreasing trends in the dry and wet spells were reported by a number of other studies for different areas in Ethiopia (Seleshi and Zanke 2004; Seleshi and Camberlin 2006; Bewket and Conway 2007).

These observed trends in rainfall corroborate well with the projected changes to mid- and end-of-century periods under different emission scenarios (IPCC 2014). According to AR5, the assessment of 12 CMIP3 general circulation models (GCMs) suggests that the climate of East Africa will be wetter by the end of the twenty-first century with more intense wet seasons and less severe droughts during October–December (OND) and MAM. However, the report highlights a wide range of projections and lack of agreement in the GCM projections over Ethiopia (Conway and Schipper 2011). According to the report, in some regions such as the upper Blue Nile basin, there are differences in the direction of precipitation change by different GCMs (Elshamy et al. 2009).

4.3 Potential impacts on agriculture

In general, the trends observed in this analysis indicate that the mid- to lowlands are the areas where significant changes in the

Table 2 Trends in the seven extreme precipitation indices for 374 grids covering Ethiopia

Season	Index	Trend magnitude ^a	Decreasing ^b (%)	Increasing ^b (%)	No trend	Decreasing (mm/day)	Increasing (mm/day)
Annual	pq95	0.85 (−0.33~6.97)	4 (1% , <i>0%</i>)	350 (94% , <i>29%</i>)	20 (5%)	0.8	2.2
	px3d	0.85 (−0.33~6.97)	38 (10% , <i>0%</i>)	282 (75% , <i>20%</i>)	54 (14%)	0.4	2.3
	px5d	1.67 (−6.30~19.89)	35 (9% , <i>0%</i>)	284 (76% , <i>3%</i>)	55 (15%)	0.2	2.5
	px10d	1.63 (−7.6~26.6)	70 (19% , <i>0%</i>)	263 (70% , <i>3%</i>)	41 (11%)	0.9	2.2
	CWD	−0.038 (−0.211~0.092)	274 (73% , <i>33%</i>)	50 (13% , <i>0%</i>)	50 (13%)		
MAM	CDD	−0.033 (−1.40~0.553)	139 (37% , <i>5%</i>)	163 (44% , <i>8%</i>)	72 (19%)		
	pq95	0.21 (−1.17~2.17)	81 (22% , <i>2%</i>)	252 (67% , <i>7%</i>)	41 (11%)	1.1	1.8
	px3d	0.21 (−1.17~2.17)	147 (39% , <i>0%</i>)	179 (48% , <i>2%</i>)	48 (12%)	1.5	1.3
	px5d	−0.26 (−7.063~1.93)	197 (53% , <i>5%</i>)	140 (37% , <i>6%</i>)	37 (10%)	1.9	0.9
	px10d	−0.637 (−11.37~1.84)	216 (58% , <i>4%</i>)	106 (28% , <i>2%</i>)	52 (14%)	2.1	1
JJAS	CWD	−0.044 (−0.191~0.313)	319 (85% , <i>35%</i>)	40 (11% , <i>0%</i>)	15 (4%)		
	CDD	0.087 (−1.20~0.445)	87 (23% , <i>2%</i>)	243 (65% , <i>24%</i>)	44 (12%)		
	pq95	1.1 (−8.4~14.0)	7 (2% , <i>0%</i>)	343 (92% , <i>13%</i>)	24 (6%)	1.2	3.2
	px3d	1.18 (−8.42~14.1)	22 (6% , <i>0%</i>)	306 (82% , <i>5%</i>)	46 (12%)	0.2	2.2
	px5d	1.66 (−2.46~14.21)	40 (11% , <i>0%</i>)	306 (82% , <i>10%</i>)	28 (7%)	0.5	2.3
JJAS	px10d	1.77 (−3.55~15.96)	54 (14% , <i>0%</i>)	270 (72% , <i>14%</i>)	50 (13%)	0.7	2.5
	CWD	−0.046 (−1.504~0.169)	229 (61% , <i>25%</i>)	97 (26% , <i>2%</i>)	48 (13%)		
	CDD	0.015 (−0.481~0.560)	117 (31% , <i>5%</i>)	209 (56% , <i>16%</i>)	48 (13%)		

pq95 95th percentile of rainy day amounts (mm/day), px3d greatest 3-day total rainfall, px5d greatest 5-day total rainfall, px10d greatest 10-day total rainfall, pxcdd maximum number of consecutive dry days, pxcwd maximum number of consecutive wet days

^aNumbers indicate mean and range within parenthesis

^bNumbers indicate the number of grids showing increasing or decreasing trend. Figures in parenthesis are percent of total grids in bold and percent of total grids in which the change is significant ($p < 0.05$) in italics

amount and distribution of rainfall are taking place. These are the rift valley and eastern parts of the country. The declining trend in rainfall during the March–May period will have a serious impact on agriculture in this predominantly bimodal rainfall areas. Though the rainfall during the March–May period is always erratic with high levels of CV and high risk of crop failure, the amount and distribution of rainfall during this period will also impact the production and productivity of the crops during the June–September main rainy season through impacts on carry-over moisture, planting time and potential to grow certain crops and varieties. It is very likely that the observed declining trend in the March–May rainfall period, declining number of rainy days and increased occurrence of extreme events will have significant negative impacts on the production and productivity of agricultural systems in these densely populated areas. The increasing trend in the amount of rainfall during the period of June–September received in the predominantly pastoral Somali and Afar regions is expected to have a positive impact on the availability of fodder and also in supporting the sedentary agriculture which is increasingly practised. High levels of land degradation are one of the major problems that the highland areas with high rainfall are facing. This is expected to be more severe in the

future with the increasing trends observed both in the frequency of occurrence and in the intensity of extreme events (Sivakumar et al. 2005; Krishna Kumar et al. 2004).

Rainfall in Ethiopia is also a major contributor to flows into the Nile River. The observed increasing trends in the frequency of occurrence and magnitude of extreme events in the catchment areas will have a significant impact on the water and sediment flows into the river and on the agriculture in the downstream countries of Sudan and Egypt. These changes are also expected to increase the flood and soil erosion risks in Ethiopia which is already a hot spot for erosion-induced land degradation.

5 Conclusion

The trends observed in this study clearly indicate that substantial changes are taking place in the amount and distribution of rainfall over Ethiopia. The consistency in the trends over large spatial areas further confirms the robustness of the trends and can serve as a basis for understanding the projected changes in the climate over Ethiopia. The observed trends in rainfall are along the lines predicted by global climate change models and

will have significant impacts on agriculture, which is a highly climate-sensitive sector. The impacts of these changes can be both positive and negative. The rift valley and adjoining lowlands to the east of the rift valley are likely to be more negatively impacted while positive impacts are expected in the pastoral and semi-pastoral areas of Somali and Afar regions. In the highlands, the potential for accelerated land degradation is high. Adequate attention to adapt to these changes is required, and the national climate change adaptation plans should consider these changes while planning for adapting to projected changes in climate. Overall, the findings of this study provide critical information on current variability and trends in the amount and distribution of rainfall events over Ethiopia which is extremely useful for the planning and management of agricultural activities with reduced risk and enhanced productivity.

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