Rainfall analysis for rain-fed farming in the Great Rift Valley Basins of Ethiopia

Fitih Ademe, Kibebew Kibret, Sheleme Beyene, Mezgebu Getinet and Gashaw Mitike

ABSTRACT

Rainfall is the most important source of water for crop production in Ethiopia. However, its temporal and spatial variability is leading to serious food shortages and insecurity in the country. This study was aimed at investigating the characteristics of selected agroclimatic variables over the great Rift Valley regions of Ethiopia. Long term (1981–2010) climate data were analyzed for 17 stations selected based on agroecology representation. Selected descriptors for climate variability and the Mann–Kendall trend test were employed. Onset, cessation, length of growing period (LGP), water requirement satisfaction index and dry spell occurrence during the growing period were determined. The results showed low to very high rainfall variability (14–35%), LGP (20–256 days) and dry spell probability (50–100%) during the main season. Significant ($P \leq 0.05$) annual and seasonal rainfall trends were observed in some stations. The probability of occurrence of a dry spell during the seasons was found to be a challenge for most of the stations in the mid and low altitude areas of the basins. Consequently, seasonal water deficit was observed in these areas which hampered crop production. Area specific recommendations are thus required based on specific challenges in the study region.

Key words | dry spell, rainfall variability, seasonal water deficit

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INTRODUCTION

Rain-fed farming is the main form of crop production in Ethiopia, as for many of the neighboring regions in Africa. However, it is highly variable in most parts of the country both in terms of length of the rainy season and amount of rainfall (Mesay 2006). Natural rainfall is the main source of water for crop production because of the lesser coverage of irrigation (below 5% of the cultivated land) in the country (Awulachew *et al.* 2010) and hence rain-fed crop production is the basis for all subsistence farming in most parts of the country and the major pillar to attaining food security in the country (NMA 1996a).

Rainfall in much of the country is erratic and unreliable, and hence its variability and associated droughts have historically been major causes of food shortages and famines (Tadesse 2000 cited in Gebremichael *et al.* 2014). It seems that there is a significant relation between climate and agricultural production in terms of the timing, variability, and quantity of seasonal and annual rainfall in Ethiopia. According to von Braun (1991), a 10% decrease in seasonal rainfall from the long-term average generally translates into a 4.4% decrease in the country's food production. Hagos *et al.* (2009) also examined the impact of rainfall variability on the Ethiopian economy, and found that rainfall variability in the country led to a production deficit (20%) and increased the poverty rates (25%) which costs the economy over one-third of its growth potential.

In general, three seasons exist in Ethiopia. The first is the main rainy season from June to September, the second

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is the dry season from October to December/January, and the third is the small rainy season from February/March to May, known locally as *Kiremt*, *Bega* and *Belg* respectively (NMA 1996a; Seleshi & Zanke 2004). The major contribution of crop production to the national economy is associated with the rainfall during *Kiremt* (the main season during June to September). Krauer (1988) indicated that *Kiremt* contributes to 50–90% of the annual rainfall over the major rainfall area of the country and is responsible for 85–95% of the production of food crops.

The seasonal and annual rainfall variations in Ethiopia are the results of the macro-scale pressure systems and monsoon flows, which are related to the changes in the pressure systems (Beltrando & Camberlin 1993; NMA 1996a). The most important weather systems that cause rain over Ethiopia include Sub-Tropical Jet (STJ), Inter Tropical Convergence Zone (ITCZ), Red Sea Convergence Zone (RSCZ), Tropical Easterly Jet (TEJ) and Somalia Jet (NMA 1996a). Regional and global weather systems affecting the *Kiremt* (June–September) season include the (ITCZ), the Maskaran High Pressure in the Southern Indian Ocean, the Helena High Pressure Zone in the Atlantic, the Congo air Boundary, the Monsoon depression and Monsoon trough, the Monsoon Clusters and the Tropical Easterly Jet (Gebremichael *et al.* 2014). Between June and September, the ITCZ is located north of Ethiopia and pronounced cyclonic cells along the ITCZ are over North Africa and the Arabian Peninsula. The rest of the country comes under the influence of the Atlantic equatorial westerlies and southerly winds from the equatorial Indian Ocean. The southwest equatorial westerlies ascend over the southwestern highlands and produce the main rainy season over most parts of the Ethiopian highlands. The southerly winds from the Indian Ocean, despite the fact that they lose their moisture over the East African highlands, are blowing over the eastern lowlands of Ethiopia where their influence on rainfall is minimized (Gebremichael *et al.* 2014). During the *Kiremt* season, the maximum rainfall occurs over the central and southwestern highlands (600–1,200 mm) while the rest of the regions receive a lesser amount (Mesay 2006).

Crop production in the great Rift Valley region is predominantly rain-fed and hence is prone to risks of climate variability. Although the region is one of the more environmentally vulnerable in the country, reports show that significant rain-fed crop production has been expanded over recent decades (Jansen *et al.* 2007). Exploring options in the basins would thus be an important step to understand the nature, trend and variabilities of the climate to fully utilize its crop production potential and respond to climatic risks. Very few such studies have been carried out in these areas, of which the majority did not take into account spatial variations across different representative agroecologies. Moreover, previous studies mainly focused on area-averaged rainfall constructed from stations with different record periods. Use of these area-averaged rainfall time series constructed from varying numbers of stations involved in the analysis in time and over diverse topography may mask the true variability of rainfall (Seleshi & Zanke 2004). Clearly understanding the variability of key main season characteristics is crucial for the study basins' agricultural planning (Segele & Lamb 2005) and to optimize the use of available rainfall with respect to meeting crop water requirements. The study gave adequate attention to rain-fed agriculture as a key element in food security in Ethiopia (NMA 1996b). Hence, this paper presents the nature, characteristics and variability of the most crucial climatic variable, rainfall over the great Rift Valley regions of Ethiopia during the main growing season.

MATERIALS AND METHODS

Description of the study area

The Ethiopian Rift Valley, which is part of the East Africa great Rift Valley system, dissects the highland plateau from northeast to southwest and tilts from the center in a northeasterly and southwesterly direction to comprise the basins and its features. It consists of four distinct basins, namely Awash, Omo-Gibe, Rift Valley Lake and Danakil basins. The study basins extend from the northeastern Awash basin to the southwestern edges of rift valley lakes and Omo-Gibe Basins. The area is situated roughly between 5.5–12°N latitude and 36–44°E longitude with an estimated total area of 18,219,000 hectares (MoW&E 2010), which is nearly 20% of the total land area of the country. The study focuses on three out of the four basins based on their agricultural importance in the Awash, Omo-Gibe and Rift Valley Lake Basins and is hereafter referred to as the Great Rift Valley Basins (GRVB) of Ethiopia.

The basins consisted of several major agroecological areas (Figure 1) from the arid lowlands to the sub-humid and humid highlands (MoARD 2005). The basins receive an annual total rainfall of about 150 mm at some locations in the northeastern arid lowlands to more than 1,900 mm in the sub-humid high-altitude edges of the basins. Similarly, the mean annual temperature also varies from 10 °C at higher altitudes of parts of the Rift Valley Lake Basins to higher than 29 °C in the lowlands of the study basins (MoWR 2006; MoW&E 2010). The climate of the basins varies as a function of altitude, angle of the sun, distance from oceans, terrain and other factors, such as influence of inter-tropical convergence zone (MoW&E 2010).

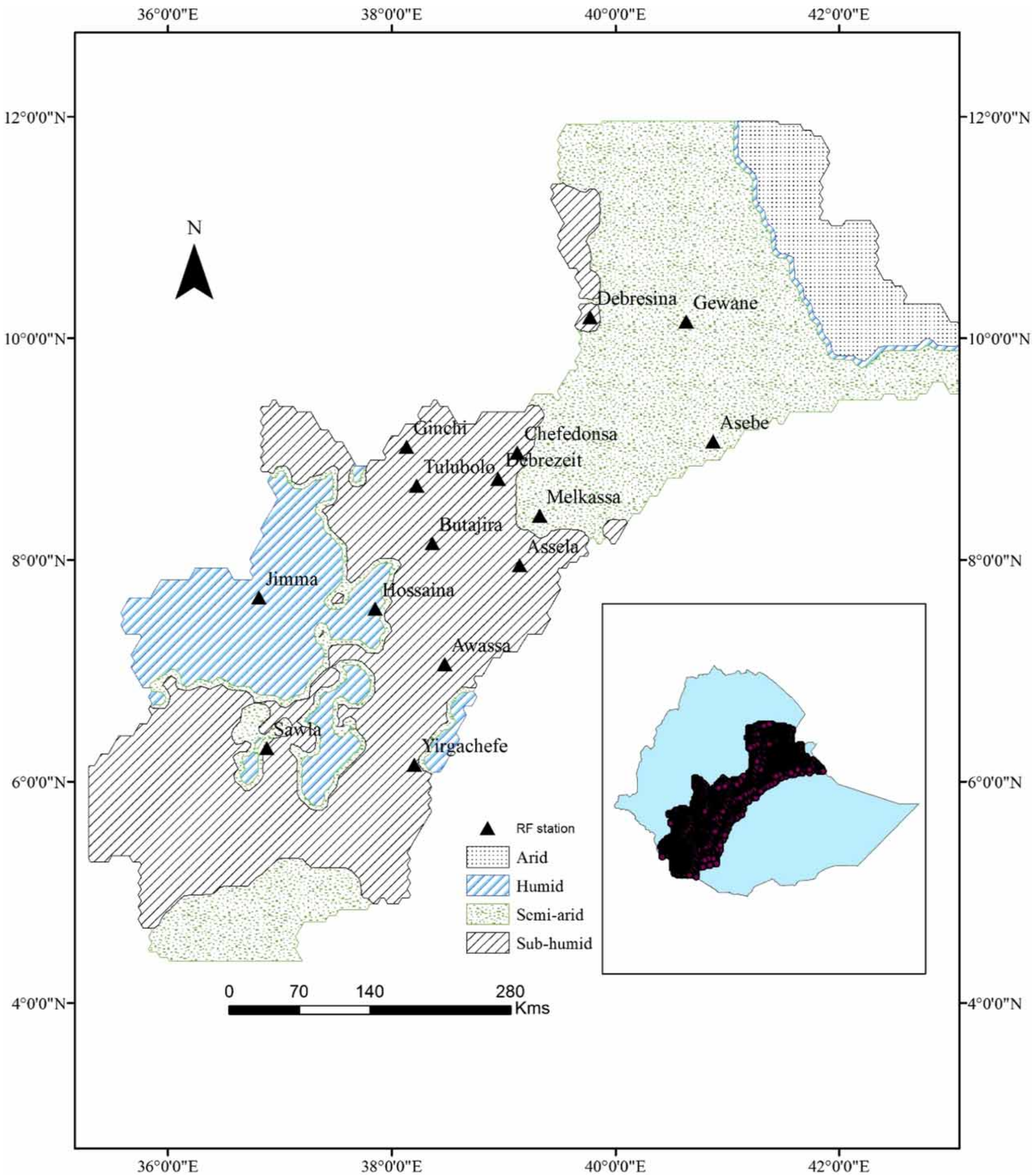

Figure 1 | Agroecological map of the study basins (source: IFPRI (HarvestChoice 2015)).

Data sources

Climate data

Daily measured weather data of 17 representative stations was obtained from the National Meteorological Agency of Ethiopia (www.ethiomet.gov.et) for the period 1981–2010 (Table 1). The collected variables include temperature (maximum and minimum), rainfall, relative humidity, wind speed (2 m) and sunshine hours. All the collected variables were used to estimate daily evapotranspiration using the widely accepted Penman–Monteith method (Allen *et al.* 1998).

Soil and crop data

Soil parameters required for analysis (water holding capacity and soil depth) were obtained from Africa Soil Information Service (AfSIS) (www.africasoil.net), the soil database was gridded over $0.25 \times 0.25°$ grids for the study locations. The parameters obtained were then checked for their representativeness for some of the stations with available measured data. Crop data such as maize crop coefficient (Kc), root depth fraction of maize (RDf) and soil water fraction (SWf) required for estimating the seasonal water requirement satisfaction index (Stern *et al.* 1982; Senay & Verdin 2003) were obtained from the FAO database (FAO 1998).

Data analysis

Data quality and pre-processing

All the climatic data were subjected to a rigorous quality check with standard quality control tests including minimum values, maximum values, mean, number of counts, missing values, and maximum differences within a data. To prepare the series for further analyses, the missing values were generated following the first order Markov chain model using INSTAT plus (v3. 37) software (Stern *et al.* 2006). Then, the generated data were verified for their physical representativeness of the respective stations in the study sites. Homogeneity of the climate data trend was checked following Von Neumann, Pettitt, SNHT and Buishand's homogeneity test criteria. Consequently, stations which are homogeneous for at least two of the tests were considered for analysis.

Table 1 | Rainfall and temperature data for representative stations in the Great Rift Valley Basins of Ethiopia

				Rainfall data		Temperature data	
Station	**Latitude**	**Longitude**	**Elevation (m.a.s.l)**	**Period**	**Missing (%)**	**Period**	**Missing (%)**
Assebe	9.07	40.87	1,792	1981–2010	9.54		
Assela	7.95	39.14	2,413	1981–2010	8.5	1981–2010	8.1
Butajira	8.15	38.36	2,000	1981–2010	6.7		
Chefedonsa	8.97	39.12	2,392	1981–2010	5.9		
Debresina	9.87	39.75	2,800	1981–2010	4.7		
Debrezeit	8.73	38.95	1,900	1981–2010	3.4		
Gewane	10.15	40.63	568	1986–2010	9.9	1986–2010	10.0
Ginchi	9.02	38.13	2,132	1981–2010	3.9		
Hawassa	7.06	38.47	1,694	1981–2010	0.03		
Hossaina	7.56	37.85	2,307	1981–2010	4.1		
Jimma	7.66	36.81	1,718	1981–2010	2.0	1981–2010	1.5
Melkassa	8.4	39.32	1,540	1981–2010	0.03	1981–2010	9.6
Sawla	6.3	36.88	1,347	1981–2010	8.13		
Tulubolo	8.67	38.22	2,190	1988–2010	4.8		
Yirgachefe	6.15	38.2	1,856	1981–2010	0.9	1981–2010	0.9
Ziway	7.93	38.7	1,640	1981–2010	2.8		

Climate variability analysis

Among the very many climatic variables, rainfall is highly variable both annually and seasonally affecting rain-fed crop production in the study basins. The Precipitation Concentration Index (PCI) and Coefficient of Variation (CV) were used as descriptors of rainfall variability. These descriptors have been widely used in many rainfall variability studies in Ethiopia and elsewhere (Bewket & Conway 2007; Bekele *et al.* 2016). PCI usually determines the nature of the monthly distribution of precipitation of a particular area. PCI can be analyzed using the following equation (De Luis *et al.* 2000; Bekele *et al.* 2016):

$$PCI = \frac{\sum_{i=1}^{12} Pi^2}{\left(\sum_{i=1}^{12} Pi\right)^2} \times 100\% \tag{1}$$

where Pi is the rainfall amount of the ith month. PCI values below 10 indicate uniform monthly rainfall distribution; values between 11 and 20 indicate high concentrations of monthly rainfall distribution; and values of 21 and above indicate very high concentrations of monthly rainfall distribution (De Luis *et al.* 2000; Bewket & Conway 2007; Bekele *et al.* 2016).

The coefficient of variation (CV%) is a unit-less (usually expressed in %) normalized measure of dispersion of a probability distribution. It expresses the standard deviation as a fraction of the mean and is useful when interest is in the magnitude of variation relative to the size of the observation (Bekele *et al.* 2016):

$$CV = \frac{S}{X} \times 100\% \tag{2}$$

where CV is the coefficient of variation; X is the average long-term rainfall and S is the standard deviation of rainfall. The CV was used to compare the long-term variation of wet season rainfall to that of individual years.

Trend analysis

The Mann–Kendall test was employed to look at the existence of statistically significant trends in the observed agro-metrological variables (Partal & Kahya 2006) and the magnitude of the trend was assessed using Sen's method (Salmi *et al.* 2002). The study investigated the presence of a monotonic increasing or decreasing trend of the climate variable over years for observed precipitation of the selected stations in the basin.

Given a dataset consisting of X values with sample size n, the Mann–Kendall calculation begins by estimating the S statistic (for a detailed description see Gabriel (2013) and Bekele *et al.* (2016)):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(Xj - Xi) \ldots\ldots\ldots\ldots\ldots\ldots for\, j > i \tag{3}$$

For any sample with $n \geq 8$, the distribution of S approaches the Gaussian form with mean equating to zero and the variance $V(S)$ given by:

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{m=1}^{n} ti(m-1)(2m+5)m}{18} \tag{4}$$

where ti is the number of threads of length m.

The statistic S is then standardized (Z value) and its significance can be estimated from the normal cumulative distribution function and given by the following equation:

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & S < 0 \end{cases} \tag{5}$$

The decision to either reject or accept the null hypothesis is then made by comparing calculated Z with the critical value at a chosen level of significance. Sen's Slope Estimator is also a commonly used non-parametric test by which true slope (change per year) of a trend is estimated (Salmi *et al.* 2002; Bekele *et al.* 2016). Sen's test is used when the trend is assumed to be linear, i.e.:

$$f(t) = Qt + B \tag{6}$$

where $f(t)$, is an increasing or decreasing function of time, i.e. the trend Q is the slope and B is the intercept (constant). The slope of each data pair Qi was calculated as:

$$Qi = \frac{Xj - Xk}{j - k} \tag{7}$$

where $j > k$ and, if there is n number of Xj in the time series, as many as $N = (n(n-1)/2)$ slope estimates of Qi are obtained. Then the values of Qi are ranked from small to large; the median of which is the Sen's slope (Q):

$$Q = \begin{cases} Q_{\left[\frac{N+1}{2}\right]}, & \text{if } N \text{ is odd} \\ \left(Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+1}{2}\right]}\right), & \text{if } N \text{ is even} \end{cases} \quad (8)$$

The initial value of the Z test statistics S is assumed to be zero, implying no trend. If a data value from a later time period is found to be greater than the data value from an earlier time period, then S is incremented by one. On the other hand, if the data value from the later time period is lower than that of the earlier period, the Z test statistic S is reduced by one. The overall result of all increments and decrements provides the final S value which lies between −1 and +1. The null hypothesis of the Z test is that no change has occurred during the time (no trend), whereas the alternative hypothesis of the Z test is that a significant change has occurred over the time.

Determination of onset, cessation and length of growing period

Objective criteria have been proposed in many studies for determining dates of the *Kiremt* rainy season onset, cessation, and length of growing period (LGP). In general, rainy season onset determination is based on the exceedance of single- or multi-day rainfall amount thresholds (wet spells), often in conjunction with the absence of subsequent rainless periods (Segele & Lamb 2005). According to Stern *et al.* (2006), the earliest start of the growing season was determined as the first occasion when the rainfall accumulated within a 3-day period was 20 mm or more that was not followed by greater than 9 days of dry spell length within 30 days from planting day. The condition of having no dry spell of more than 9 days after the start of the growing season eliminates the possibility of a false start to the season (Gebremichael *et al.* 2014). Various authors used similar criteria in assessing the start of the growing season (Barron *et al.* 2003; Stern *et al.* 2006; Kassie *et al.* 2013; Gebremichael *et al.* 2014; Bekele *et al.* 2016). The end of the growing season is mainly dictated by stored soil water and its availability to the crop after the rainfall stops. Stern *et al.* (2006) defined the end of the season as the first date on which soil water is depleted and reaches zero. However, this definition was modified when extended dry periods of more than 20 days occurred in mid-season, after which persistent rains returned. To avoid erroneously interpreting such dry-spells as cessation, the above cessation criterion was 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 (Segele & Lamb 2005). In addition, daily average evapotranspiration (Penman–Montieth) and the maximum soil water holding capacity of the top 60 cm depth were considered for calculation of water balance for each site (Table 2). The LGP was determined by subtracting the potential onset date from the end date.

For the study of dry days as well as the probability of receiving rain, a 3 mm rainfall threshold was selected conservatively for rain-fed agricultural water management purposes (Reddy 1990). Accordingly, to quantify the dry-spell likelihood, daily rainfall was fitted to a simple first order Markov chain model to determine the probability of dry spell occurrence for 3, 5, 8 and 11 days during the main growing season (Stern *et al.* 2006).

Table 2 | Soil parameters used for water balance estimation (derived from AfSIS soil database)

Station	Soil depth (cm)	WHC (mm/m)	Station	Soil depth (cm)	WHC (mm/m)
Assebe	200	249	Hawassa	200	326
Assela	100	249	Hossaina	200	305
Butajira	200	301	Jimma	100	282
Chefedonsa	100	214	Jinka	200	282
Debresina	200	300	Melkassa	200	257
Debrezeit	100	278	Tulubolo	100	223
Gewane	200	252	Yirgachefe	200	246
Ginchi	200	205	Ziway	200	262

Determination of water requirement satisfaction index

The spatially explicit water requirement satisfaction index (WRSI) is an indicator of crop performance based on the availability of water to the crop during a growing season. WRSI is the ratio of seasonal actual crop evapotranspiration (AETc) to the seasonal crop water requirement, which is the same as the potential crop evapotranspiration (PETc):

$$WRSI = \frac{\sum AETc}{\sum PETc} \times 100\% \quad (9)$$

AETc represents the actual amount of water withdrawn from the soil water reservoir where shortfall is relative to potential crop evapotranspiration (PETc) which is calculated by a function that takes into consideration the amount of available soil water. PETc denotes crop specific potential evapotranspiration after an adjustment is made to the reference crop potential evapotranspiration (PET) by the use of appropriate crop coefficients (Kc) and is obtained by:

$$PETc = PET * \mathrm{Kc} \quad (10)$$

Soil water content (SW) was estimated through a simple mass balance equation where the total volume is defined by the water holding capacity (WHC) of the soil in the effective root zone of the crop. Each time step's new SW is obtained after determining the actual extraction by the crop (AETc). To determine AETc, dekadal rainfall (PPT) is first added to the existing SW to produce a plant-available-water (PAW) value:

$$PAWi = SW(i-1) + PPTi \quad (11)$$

Depending on the plant available water (PAW) in the 'bucket', the value of AETc is determined by the following set of functions (Senay & Verdin 2003):

$$AETC = \begin{cases} PETc, & when\, PAW \geq SWC \\ \frac{PAW}{SWC} * \mathrm{PETc}, & when\, PAW < SWC \\ PAW, & when\, AETC > PAW \end{cases} \quad (12)$$

SWC (mm) is the critical soil water level in the 'bucket' below which AETc will be less than PETc. SWC varies by crop and growth stage according to the following equation:

$$SWC = WHC * \mathrm{SWf} * \mathrm{RDf} \quad (13)$$

SWf is the fraction of WHC that defines the available soil water level below which AETc becomes less than PETc during the mature stage of the crop (root depth fraction, or RDf = 1.0). For maize the SWf is 0.45 (FAO 1998).

The final soil water content at each cycle was then obtained by:

$$SWi = SW_{(i-1)} + PPTi - AETci \quad (14)$$

where SW is the final soil water content at the end of simulation period, PPT is precipitation, and i is the time step index.

At the end of the crop growth cycle, or up to a certain dekade in the cycle, the respective sums of crop actual evapotranspiration (AETc) and crop potential evapotranspiration (PETc) are used to calculate WRSI. PETc is calculated from temperature, relative humidity, wind speed and sunshine hours using the FAO Penman–Monteith equation (Allen et al. 1998). A case of 'no deficit' will result in a WRSI value of 100, which corresponds to the absence of yield reduction related to water deficit. Any WRSI value below 100% indicates soil moisture level satisfying the crop at that instant and a seasonal WRSI value less than 50 is regarded as a crop failure condition (Smith 1992).

Maize crop with 90 (early maturing), 120 (medium maturing) and 180 days (late maturing) was used to determine the seasonal water requirement depending on the corresponding LGP of each site. Kc values of maize derived for each growing stage were linearly interpolated into daily values using INSTAT software. Published values of Kc for maize (FAO 1998) are available for critical points in a crop phenology and intervening values. For the study, maize Kc values were taken as 0.3, 0.3, 1.20, 1.20, and 0.35 for the times corresponding to 0, 16, 44, 76, and 100% of LGP, respectively.

RESULTS AND DISCUSSIONS

Precipitation characteristics and variability in the GRVB

The GRVB consist of various agroecology with varying patterns of precipitation. Stations with bimodal rainfall pattern with rainfall picks in April (February–May, short season also known as '*Belg*') and July (Jun–Sept also known as '*Kiremt*') are presented in Figure 2 and similar stations with bimodal pattern with picks at April (March–May also known as 'Spring rain') and October (September–November also known as 'Autumn rain') are presented in Figure 3. A mono-modal pattern of rainfall with long '*Kiremt*' which extends from March to November (for example, Jimma) is depicted in Figure 2. These variations in the study basins may be explained by the geographical positions of the stations with respect to the equator. Mutai & Ward (2000), for example, reported Spring rain is the major rainfall period for the near-equatorial regions of extreme southern and southeastern Ethiopia that are associated with the long rainy season of equatorial East Africa. On the contrary, the northern and northeastern stations, which receive their monsoon rains that start during May or June and extend to September/October, are related to the northward migration of the sun away from the equator.

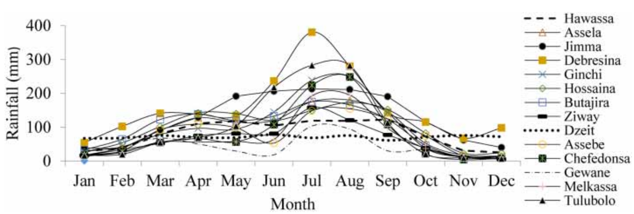

Figure 2 | Rainfall characteristics of stations with bimodal short (February–May) and long (June–September) season in the study basins.

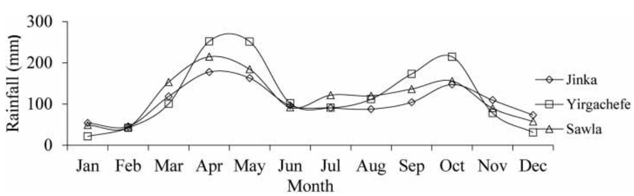

Figure 3 | Characteristics of stations with long (spring) and short (autumn) rainfall in the study basins.

The long-term annual mean rainfall of the basins varied from 502.9 mm in the arid parts of the basins to 1,890 mm. The main growing season received 59% of the total annual rainfall while the short season contributed to 30% of the total rain received by the basins. The highest main season rainfall was recorded in Jimma (1,410.9 mm) which contributed to 92.5% of the total annual rainfall received by the station. Debresina (1,051.6 mm) and Tulubolo (899.6 mm) received the highest main season rainfall next to Jimma. The contributions of the main season rain of these stations are, respectively, 55 and 75% of the total annual rainfall of the corresponding areas. The lowest main season rainfall was recorded at Gewane (245.1 mm) which will be challenging to execute rain-fed agriculture. Similarly, the short season rainfall also varied in the study basins. The highest values were recorded at Debresina (515.5 mm) and at Yirgachefe (456.6 mm) while the lowest was at Gewane (187.6 mm). Describing stations by the total rainfall alone may sometimes mislead agricultural planners for rain-fed crop production and thus, the nature of its year-to-year distribution would be equally important. The coefficient of variation (CV in %) is the most widely used statistical measure to understand the inter-annual variabilities of rainfall distribution.

The rainfall of stations in the study basins showed both temporal and spatial variabilities. The total annual rainfall of stations showed variability ranging from low to high. According to Hare (1983), the coefficient of variation (CV) of stations is classified as low for below 20% CV, high for CV in the range of 20–30% and more than 30% is regarded as very high variability (Table 3).

The coefficient of variation of the annual, main and short season rainfall ranged from low to very high. It can be noted that half of the basins fall under low variability and the other half of the selected stations fall under high variability in terms of their annual total rainfall. Unlike the annual total rainfall of stations, the seasonal rainfall showed a high degree of variability. Accordingly, only 25% of the stations fall under low variability for the main season rainfall. The majority of the stations fall under high (50%) to very high (25%) ranges (Table 2). The short season is very prone to risk for rain-fed agriculture and almost all of the selected stations in the basins clearly indicate very high (80%) to high (20%) ranges of rainfall

Table 3 | Rainfall (mm) variability characteristics of selected stations in the GRVB, 1981–2010

		Annual		Main season		Short season		
Station	**Alt.(m)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**PCI (%)**
Assebe	1,792	928	25.03	477.3	30.4	329.5	46.4	11.7
Assela	2,413	1,093.8	14.5	620.2	16.9	372.7	39.2	11.8
Butajira	2,000	1,147.7	22.5	597.1	25.2	446.6	42.1	11.2
Chefedonsa	2,392	943.1	24.4	682.4	23.0	205.1	55.8	16.5
Debresina	2,800	1,890.1	25.6	1,051.6	34.5	515.8	36.5	11.1
Debrezeit	1,900	850.8	14.8	283.1	23.8	282.4	25.9	8.4
Gewane	568	502.9	23.5	245.1	36.9	187.6	45.5	12.6
Ginchi	2,132	1,177.7	21.6	774.4	23.1	311.4	44.3	13.7
Hawassa	1,694	969.6	14.2	464.8	23.8	347.7	26.1	10.2
Hossaina	2,307	1,156.9	17.2	593.6	15.1	437.8	29.7	10.7
Jimma	1,718	1,525.7	12.7	1,410.9	13.7	NS	NS	10.8
Melkassa	1,540	814.9	17.1	547.4	18.9	194.7	46.6	15.1
Sawla	1,347	1,416.3	14.6	551.9	23.7	381.7	32.1	9.9
Tulubolo	2,100	1,196.9	25.2	899.6	32.1	245.1	40.5	16.7
Yirgachefe	1,856	1,468.7	24.2	604	29.1	456.6	33	11.7
Ziway	1,640	749.1	19.8	437.3	22.3	241.7	43.2	12.5

NS, No short season (monomodal).

variability. Similar results were published by Kassie *et al.* (2013), Gebremichael *et al.* (2014) and Bekele *et al.* (2016) for CRV in South Ethiopia and Awash Basin, respectively. The authors indicated a high coefficient of variation (CV% >30) for *Belg* season rainfall than its corresponding *Kiremt* season. Seleshi & Zanke (2004) emphasized the causes of total and seasonal inter-annual variability of precipitation over Ethiopia. They indicated the forward and retreat pace of the African sector of the intertropical convergence zone (ITCZ) and their ending and beginning times vary annually, causing most of the inter-annual variability in rainfall over Ethiopia. The migration of ITCZ is sensitive to variations in the Indian Ocean surface temperature that varies from year to year, influencing the characteristics of the season in the region as well as episodes of El Niño Southern Oscillation and La Niña (Dessu & Melesse 2013). The Precipitation Concentration Index (PCI) values also indicated that in most of the stations the values were more than 10%, indicating the presence of seasonality in rainfall distribution (Bewket & Conway 2007; Bekele *et al.* 2016) in the study basins (Table 3).

Rainfall trends of the GRVB

The annual rainfall showed no significant changes during the recorded period, except at Melkassa where a highly significant ($P < 0.01$) increase of 9.88 mm/yr was observed (Table 4). The majority of the stations showed a non-significant positive trend in the range of 0.66–4.25 mm/yr while some stations showed a non-significant negative trend in the range of 0.55–3.17 mm/yr. Similarly, the main season variability showed a non-significant trend at all stations in the study basin, except for Gewane (+6.55 mm/yr) and Melkassa (+5.57 mm/yr). The most hydro-meteorological time series are characterized by a high variability and large scale random variation about the mean value, although monotonic change in a mean value defined as trend is sometimes observed in such series (Duggal & Sons 2000). The results are in agreement with reports from other studies in different parts of the country. For instance, Bekele *et al.* (2016) reported that the *Kiremt* season rainfall exhibited a non-significant increasing trend in eight out of 12 stations, but three out of 12 showed statistically

Table 4 | Annual and seasonal rainfall trend (mm/yr) of selected stations in the GRVB

	Annual			Main season			Short season		
Station name	**Z**	**Q**	***P*-value**	**Z**	**Q**	***P*-value**	**Z**	**Q**	***P*-value**
Assebe	–0.04	–1.69	0.751	0.17	3.57	0.179	–0.18	–5.71	0.169
Assela	–0.14	–3.17	0.272	–0.13	–2.58	0.321	–0.08	–1.86	0.572
Butajira	–0.002	–0.55	1.000	0.13	3.42	0.339	–0.12	–4.64	0.357
Chefedonsa	0.03	2.23	0.832	0.08	1.7	0.572	–0.01	–0.25	0.944
Debresina	0.06	4.25	0.672	0.15	7.43	0.256	–0.22	–7.54	0.087
Debrezeit	0.03	0.89	0.859	–0.04	–0.43	0.777	0.01	0.2	0.944
Gewane	0.18	4.03	0.155	0.41	6.89	**0.001**	–0.29	–3.67	**0.024**
Ginchi	–0.09	–3.0	0.479	0.08	1.85	0.556	–0.20	–4.17	0.126
Hawassa	0.04	0.66	0.762	–0.11	–1.45	0.402	–0.07	–1.57	0.621
Hossaina	0.09	3.33	0.524	0.08	1.76	0.551	0.01	0.39	0.944
Jimma	0.11	3.85	0.396	0.14	3.64	0.304	[a]	[a]	[a]
Jinka	0.07	4.05	0.621	0.09	1.27	0.509	0.08	1.57	0.556
Melkassa	0.40	9.88	**0.001**	0.31	5.57	**0.018**	0.09	1.30	0.509
Sawla	–0.05	–2.22	0.697	–0.13	–2.29	0.339	–0.04	–0.57	0.777
Tulubolo	–0.01	–0.80	0.944	0.05	2.00	0.697	–0.12	–2.33	0.353
Yirgachefe	–0.04	–2.7	0.777	–0.14	–3.08	0.272	–0.06	–2.1	0.646
Ziway	0.13	3.01	0.321	0.05	0.81	0.724	–0.02	–0.4	0.887

[a]Indicates station with one long season, bold *P*-values indicate significance at 0.05/0.01 alpha level.

significant trends in the Awash basin of Ethiopia. Cheung *et al.* (2008) reported a decline in the *Kiremt* rainfall for watersheds located in the southwestern and central parts of the country, but also their observed changes were not statistically significant for any of the watersheds examined. Few stations in south Ethiopia showed a negative significant trend in annual rainfall (Gebremichael *et al.* 2014). Similarly, Osman & Sauerborn (2002) also found negative anomalies with *Kiremt* rainfall frequently being lower than the long-term average for the north central highlands of Ethiopia. On the other hand, Kassie *et al.* (2013) reported a non-significant rainfall trend for the CRV stations, except for one station out of 16.

Despite the absence of significant trends in rainfall patterns, the high inter-annual variability and season to season variation implies a challenge to rain-fed agriculture. The declining trend in *Kiremt* rainfall and increase in daily rainfall intensity disadvantages rain-fed crop production. Various studies indicated that the amount and temporal distribution of rainfall is generally the most important determinant of inter-annual fluctuations in crop production in Ethiopia and has had significant effects on the country's economy and food production for the last three decades (World Bank 2006; Bewket & Conway 2007; Hellmuth *et al.* 2007; Araya & Stroosnijder 2011; Conway & Schipper 2011; Demeke *et al.* 2011; Kassie *et al.* 2013; Bekele *et al.* 2016). The inter-annual and intra-seasonal rainfall variabilities in the GRVB are accompanied by significant warming trends in temperature, which can add stress to crop growth during periods of already high temperatures.

Main growing season characteristics of the study basins

Onset and cessation

The dates of the main growing season onset and cessation vary across the representative station within the GRVB of Ethiopia. Mean potential onset dates ranged from Julian date number 83–167 (which is from March 23 at Jimma to June 15 at Melkassa) (Figure 4). Earlier onset of the main growing season may be associated with the position of

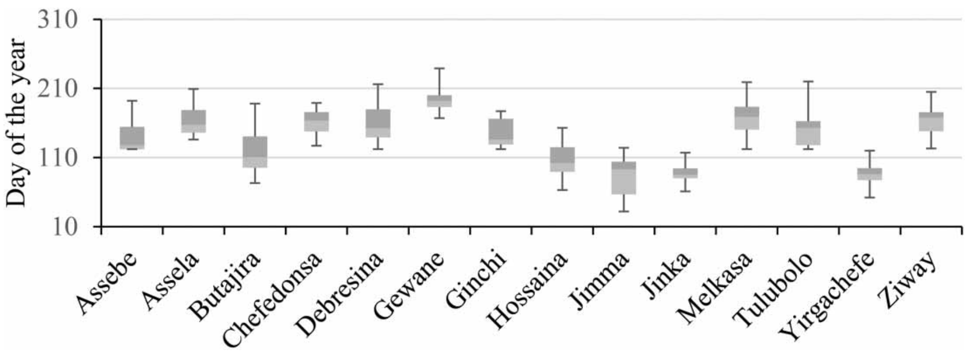

Figure 4 | Onset date of the main rain season of stations selected based on different agroecological representation in the study basin (1981–2010).

the station from the equator where the position of the inter-tropical convergence zone (ITCZ) roughly reaches the equator during the spring equinox. The southern part of the basin receives the spring rains (Mutai & Ward 2000) in March which describe early onset in those stations. Considerable annual variations in the main growing season exist over all the stations. The standard deviation of onset ranged from ±11.4 to ±32.4 days. The higher standard deviation of the onset date of the seasons implies that patterns could not be easily understood and consequently decisions pertaining to crop planting and related activities will be made with high risk.

Similar reports were also made by Segele & Lamb (2005) in their thorough investigation of climatic patterns for the whole of Ethiopia. They revealed that the mean *Kiremt* onset advances gradually northeastward from southwestern regions. The rains start in early-to-mid March over southwestern Ethiopia and progress northward to cover the western half of the country by mid-June. At the other extreme, the northeastern-most regions do not receive their first rain until mid-to-late July, with the latest mean onset being over the dry regions of the Rift Valley.

The end of the season is governed by stored soil water and its availability to the crop after the rainfall stops. Mean dates of cessation vary from Julian date number 222–322 (from August 9 to November 17) (Figure 5). Unlike the start of the season, the end date did not show variations for the majority of stations considered. However, some stations showed high variability in their cessation of the main growing season (standard deviation up to 64 days at Yirgachefe). Similarly, Assebe, Debresina and Jinka also showed uncertainties in season cessation. The annual variabilities in predicting the end of the season may affect farmers' decisions to select high yielding, long maturing crops.

Studies by Segele & Lamb (2005) indicated that different ranges of temporal variability exist in the mean onset and cessation date depending on the geographical location of the stations, but orographic effects should not be undermined. Stations in the southwest parts of the basin showed higher variability in cessation dates than the northern and

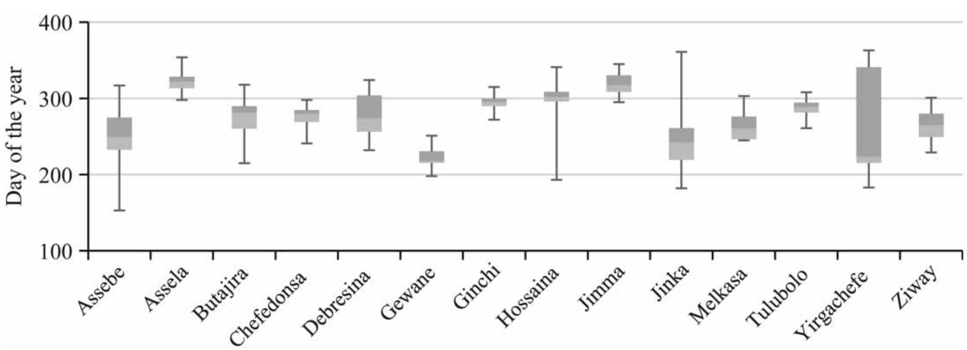

Figure 5 | Cessation date of the main season of stations representing different agroecology of the study basins (1981–2010).

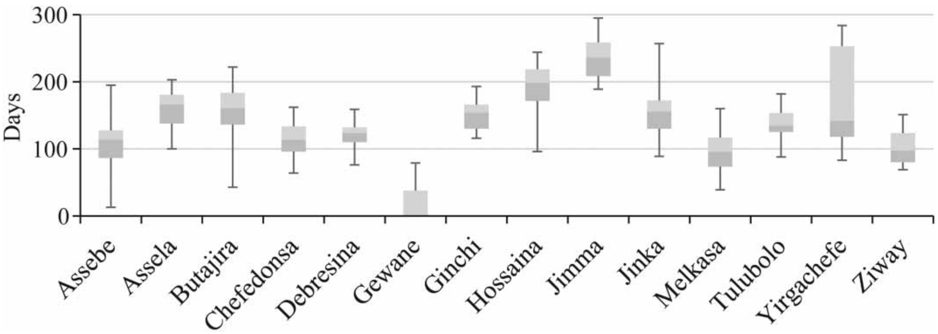

Figure 6 | Length of growing period (LGP) of selected stations for the main season (1981–2010).

northeastern stations. They also emphasized that within the larger-scale climate system context, the southwestward *Kiremt* retreat is associated with the seasonal weakening of the eastern Atlantic and western Indian ocean monsoon systems and the southward displacement of the near equatorial trough/ITCZ.

Length of growing period

The mean potential LGP of the main growing season ranged from 20 to 236 days (Figure 6). The standard deviation of LGP for *Kiremt* growing season ranged from 20 to 45 days. The results revealed high inter-annual variability of LGP, which can be explained by high inter-annual variability in the onset and cessation dates in the season. Similarly, the results of Bekele *et al.* (2016) indicated early/delayed onset and/or corresponding delayed/early cessation resulting in the annual variation in the duration of the growing season in the Awash basin of Ethiopia. High variability (CV >20%) in the seasonal rainfall may have resulted in the variability of the main season length of the growing period (Table 3). Annual variation in the length of the growing period may pose a serious challenge to plan and implement rain-fed crop production.

Trends of the main growing season

The Mann–Kendal trend test revealed that during the 30-year period (1981–2010) almost all of the selected stations of the basin did not show either an increasing or a decreasing trend ($P \leq 0.05$) in the LGP of the main season (Table 5). However, Debresina station showed a decrease of 10 day/decade ($P \leq 0.1$) for the last 30 years, which can be interpolated as 30 days' loss from the main season during the analysis period. At the majority of the stations, the slopes indicated an increment in their respective LGP durations ranging from 1 to 42 days during the 30-year period, although a non-significant

Table 5 | Trends of main season LGP (days/yr) of selected stations in the GRVB

	LGP				LGP		
Station name	**Z**	**Q**	***P*-value**	**Station name**	**Z**	**Q**	***P*-value**
Assebe	0.08	0.43	0.544	Hossaina	0.02	0.06	0.915
Assela	0.09	0.39	0.498	Jimma	0.17	1	0.913
Butajira	–0.04	–0.35	0.748	Jinka	0.20	1.41	0.123
Chefedonsa	0.11	0.75	0.396	Melkassa	0.13	0.81	0.335
Debresina	–0.25	–1	0.054*	Tulubolo	–0.05	–0.11	0.721
Gewane	0.06	0	0.663	Yirgachefe	–0.13	0.93	0.326
Ginchi	–0.18	–0.6	0.18	Ziway	0.02	0.04	0.886

*Significance at 0.1 alpha level.

trend was observed ($P \leq 0.05$). However, the remaining few stations showed a non-significant ($P \leq 0.05$) decrement in LGP ranging from 3 to 18 days during the record period. Reports by the World Bank (2006) provided evidence that uncertainty of the growing season is one of the main challenges for rain-fed crop production indicating that the late start of the *Kiremt* in 1997 caused a reduction in average yield of cereals by 10% across Ethiopia. Camberlin & Okoola (2003) also observed a 25–30% maize yield reduction in Kenya due to a 20-day delay of the main rainfall season.

Dry spell occurrence during the main growing season

The probability of dry spells for 3, 5, 8 and 11 consecutive days that occurred during the growing season was analyzed for selected representative stations of the GRVB (Figure 7). The analysis showed that the arid parts of the basins, such as Gewane, experienced a high probability of a dry spell of 3 days (100%) and 5 days (more than 70%) during the main growing season. Humid areas such as Jimma showed a probability of a dry spell occurrence of 3 days (above 50%) and 5 days (lower than 20%) during the main growing

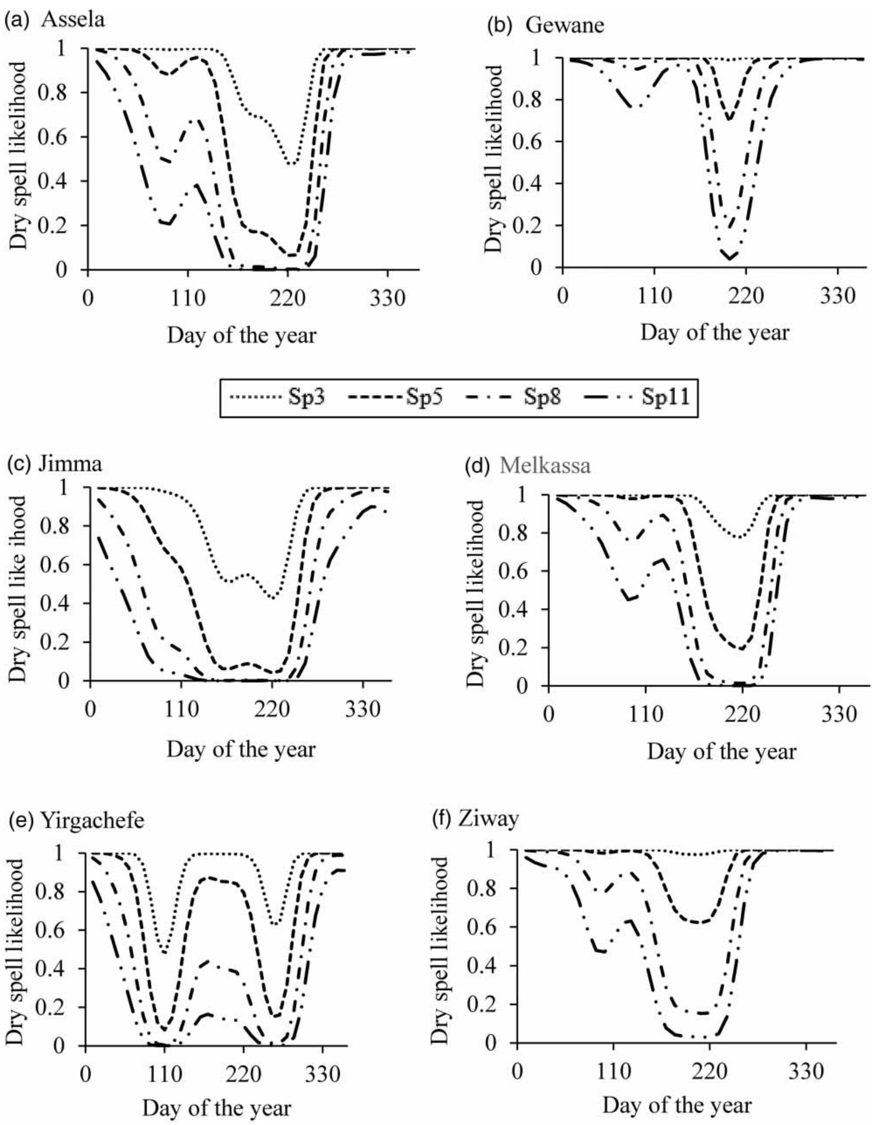

Figure 7 | Probability of dry spell occurrence of 3, 5 8 and 11 days of selected stations in the GRVB.

season. The semiarid areas (Melkassa and Ziway) showed a relatively high probability of 3 and 5 days of dry spell in most of the years during the middle of the growing season, and Ziway was highly vulnerable in most of the years. A length of 8 and 11 consecutive days in the main season occurs rarely (below 20%) regardless of the stations' agroecology. However, the short season suffers from long dry spells, which makes the season unreliable for rain-fed agriculture. Similar reports by Kassie *et al.* (2013) indicated that the CRV is characterized by intermittent dry spells with higher probabilities of occurrence during the growing season. Most of the crops cultivated in the CRV are most likely to be exposed to moisture stress. For instance, at Ziway, there is a 26% chance of getting dry spells of longer than 7 days at the early growth stage of a crop and the probability is higher (92%) during the late development stage of the crop. Studies by Segele & Lamb (2005) and Araya & Stroosnijder (2011) also indicated that dry spells of about 10 days length were among the major causes of crop failure in the rain-fed farming systems of Ethiopia. The latter authors indicated that 20% of crop failure in drought prone parts of Ethiopia was due to dry spells during the growing season. The increased probability of dry spells at all stations in late August and thereafter may be related to the southward shift of the ITCZ (Araya & Stroosnijder 2011). On the other hand, Segele & Lamb (2005) indicated that long and consecutive dry spells were strongly related to a major downturn in dew point, abnormally high temperatures, and easterly winds throughout the troposphere beneath a weak tropical easterly jet.

Seasonal water requirement satisfaction of the main season

The main season's performance in terms of water demand and its supply was evaluated for rain-fed maize during the 1981–2010 period. The performance was analyzed for late, medium and early maturing maize planted under two planting windows (May and June). The results of selected representative stations are depicted in Figure 8. The semi-arid areas of the basins, such as Melkassa and Ziway (Figure 8(a)–8(d)), suffered from moisture deficit during the growing season. At Melkassa, medium maturing (120 day) maize planted in the May planting window experienced mild moisture deficit (WRSI <80%) in most of the years (46.7% of the years) compared to the same maize cultivar planted during the June planting window (26.7% of the years). A seasonal WRSI value of less than 50 is regarded as a crop failure condition (Smith 1992; Martin *et al.* 2000). Similarly, early maturing maize planted earlier in May (three out of five years) was severely affected by moisture deficit compared to when it was planted in

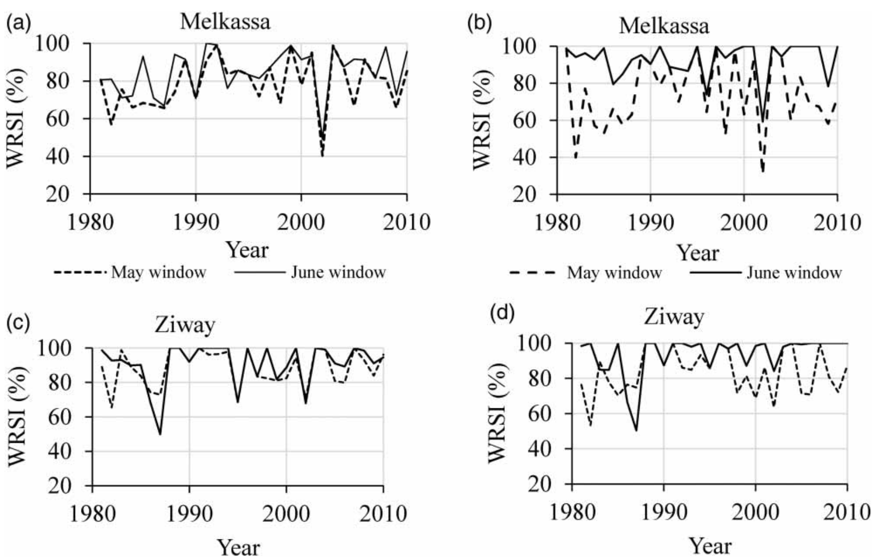

Figure 8 | Seasonal WRSI for (a) medium and (b) early maturing maize at Melkassa and (c) medium and (d) early maturing maize at Ziway for the May and June planting windows.

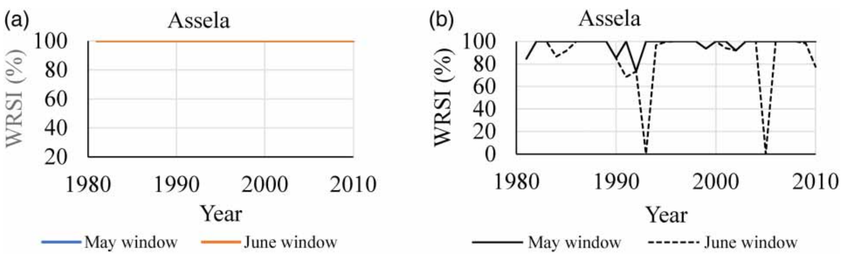

Figure 9 | Seasonal WRSI of medium (a) and late maturing maize (b) under May and June planting window at Assela.

June at Melkassa. It can also be noted that planting short maturing varieties of maize earlier in the season may lead to complete crop failures or significant yield reductions. In contrast to the results at Melkassa, at Ziway medium maturing cultivars of maize may benefit if planting takes place early in the season in May rather than planting in June. However, for early maturing cultivars, the risk of experiencing moisture deficit is higher (WRSI <80%) for most of the seasons when planting takes place in May (40% of the years) than in June (only 6.7% of the year).

Medium and high rainfall areas, unlike low rainfall areas, experienced very little risk of seasonal moisture deficit during the growing season. An example is displayed in Figure 9(a) where a case of 'no deficit' was obtained at Assela resulting in a WRSI value of 100, which corresponds to the absence of yield reduction related to water deficit for medium maturing cultivars when planted either in early May or June. However, the late maturing cultivars in the same location were impacted by severe moisture deficit in one out of 15 years leading to complete crop failures if planted in June rather than when planting takes place in the May planting window (Figure 9(b)). The WRSI calculated for 90- and 120-day cycled maize cultivars indicated that the effective rainfall available during the growing season was not sufficient for maximum production of the crops in most of the seasons. Kassie *et al.* (2013) indicated that crops grown in the CRV, particularly long cycled varieties, experienced water stress during the growing season and farmers need to shift to short cycled crops when rainfall is the only source of water for crop production. They further implied the necessity of improved farm management practices to support the production of short cycled varieties.

CONCLUSIONS AND RECOMMENDATIONS

Station-based analysis of the GRVB indicated that higher variation of rainfall is a characteristic feature of all stations during both the *Belg* and *Kiremt* seasons. The crop production in the short season was very unreliable compared with the main season. Time series analysis of annual and seasonal rainfall revealed a non-uniform response to both main and short seasons in the study basins. A non-significant ($P \leq 0.05$) declining trend in magnitude was observed during the short season while increasing trends were recorded at the majority of the stations during the main season. The main season contributes the lion's share of the total rainfall and corresponding crop production in the study area. The length of the growing period of the main season spatially varied from as few as 20 to as many as 236 days in the study basins. LGP trends at the majority of the stations showed a non-significant increasing trend. In some stations, however, there existed a significant declining trend in LGP signaling crop loss and/or the need for changing varieties from long maturing to medium and early maturing at the expense of yield in the future. Onset and end of the season showed high variations annually at all stations which could affect planning rain-fed farming without available supplementary irrigation. The probability of occurrence of a dry spell during the season was also a challenge for most of the semiarid and arid lowlands of the basins. Moreover, seasonal water deficit was observed for maize which has a great impact on yield reduction and even complete crop failure in some of the years in these areas. To overcome these seasonal moisture deficits in the drought prone lowlands, early planting with improved soil and water conservation practices is recommended to take advantage of each drop of rain. Similarly, *in-situ* water harvesting options should be implemented to store moisture in the soil for later use by the crop in case of prolonged dry spells and early cessations. Matching variety and planting date should be carefully made in moisture stressed areas of the basins. Moreover, in such areas supplementary irrigation is equally important. In the sub-humid and humid highlands, however, techniques which can potentially improve water productivity, such as application of optimum fertilizer, soil and water conservation practices and growing high yielding cultivars, could sustain the productivity of crops. The climate service should also provide daily and/or dekadal weather forecast information to farmers in the study areas in response to the high rainfall variability.

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