Regional Environmental Change (2023) 23:75
https://doi.org/10.1007/s10113-023-02064-9

ORIGINAL ARTICLE

Rainfall changes perceived by farmers and captured by meteorological data: two sides to every story

Lena Hubertus[1,2,3] · Juliane Groth[1] · Mike Teucher[2] · Kathleen Hermans[1,4]

Received: 4 October 2022 / Accepted: 6 April 2023

Abstract

Subsistence farmers with high dependency on natural resources are exceptionally vulnerable to rainfall changes. Besides, they are in the front row when it comes to observing these changes. Studies that systematically investigate similarities and differences between measured and perceived rainfall changes are typically limited to trends in rainfall amounts, thereby disregarding changes in extreme events, rainy season durations, and timing. We address this gap by contrasting rainfall changes perceived by subsistence farmers in the Ethiopian highlands with meteorological daily rainfall data derived from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS). We applied nine distinct metrics for rainfall dynamics, accounting for rainfall variability, including extreme events and changes in the onset and cessation of the two rainy seasons. Farmers perceived increasingly unreliable rainfall for both the short and the long rainy seasons, with later onset and earlier cessation, increasing rainfall intensity, and increasing occurrence of untimely rainfall and droughts. This partially disagrees with the CHIRPS data that indicate most significant rainfall changes for the short rainy season only. Since the early 1980s, this season has been experiencing decreasing rainfall amounts, with high variability between years and an increasingly uncertain – yet delayed – onset. In contrast, the long rainy season experienced little changes in rainfall. Our results point towards changing farmers' water availability and water demand as an explanation for the perceived deteriorating rainfall conditions. As farmers' perceptions partly diverge from meteorological observations, both data sources should be used complementarily to improve our understanding of climatic change.

Keywords Rainfall changes · Perceptions · Meteorological data · CHIRPS · Ethiopian highlands

Introduction

Climate change has severe consequences for natural resource dependent subsistence farmers. Slow onset changes with respect to precipitation pattern and temperatures, as well as increasing weather and climate extreme events have significantly affected food production and increased food insecurity (Allen et al. 2018). One of the most vulnerable and exposed regions is East Africa. Given its lacking economic, developmental, and institutional capacity, East Africa is among the regions with the most urgent need for improved adaptive capacity (IPCC 2022). Subsistence farmers in East Africa, as in many other regions in the global South, are exceptionally vulnerable to changes in climate and rainfall, but they are also uniquely positioned when it comes to observing these changes (Ayal and Leal Filho 2017). Perceptions of environmental change are considered a prerequisite for adaptation as only changes that are perceived as a risk are acted upon (Adger et al. 2009; Alessa et al. 2008). The extent to which change is perceived influences support for adaptation and alters the impacts of change (Fosu-Mensah et al. 2012; Howe et al. 2014). Consequently, misperceptions of climate risks can result in a lack of adaptation or maladaptation with potentially severe consequences for highly exposed populations (Alessa et al. 2008; Kosmowski et al.

Communicated by Angus Naylor

✉ Kathleen Hermans
KHermans@iamo.de

1 Helmholtz Centre for Environmental Research GmbH (UFZ), Leipzig, Germany

2 Department of Geoecology, Institute for Geosciences and Geography, Martin Luther University Halle-Wittenberg, Halle a/d Saale, Germany

3 Thünen Institute of Rural Studies, Braunschweig, Germany

4 Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle a/d Saale, Germany

Published online: 25 May 2023

2016). Especially in Sub-Saharan Africa, lack of access to information is one of the most important barriers to climate change adaptation (Juana et al. 2013; Tessema et al. 2013; Thompson et al. 2010).

In recent years, the number of studies investigating similarities and differences between measured and perceived rainfall changes for regions with highly variable climate conditions, such as East Africa, has grown. Meze-Hausken (2004) was one of the first who pointed at the divergence between measured and perceived rainfall changes during the second half of the last century. The author found that farmers in the northern Ethiopian highlands perceived rainfall declines during the short rainy season, which was, however, not substantiated by meteorological data. For the same region, Ayal and Leal Filho (2017) have found that farmers perceive increasingly unreliable rainfall, with delayed onset and earlier cessation of the rainy seasons, increasing rainfall intensity and an increasing occurrence of untimely rainfall and drought frequency, which was in disagreement with meteorological rainfall data. Both studies focus on long-term trends of rainfall amounts using meteorological rainfall data aggregated for each rainy season, which is acknowledged by the authors as possible explanation for the discrepancies between measurements and perceptions. Similarly, Osbahr (2011) found no major changes in rainfall amounts, intensity of rainfall events or start of the seasons based on station data from 1963 through 2008. This was in contrast to farmers perceptions, who reported changes in monthly patterns of rainfall, delayed onset and earlier cessation of rainy seasons, decreasing rainfall amounts and, increasing intensity of rainfall. The authors conclude that farmers were generally better able to remember extreme events rather than slow climate trends and that they likely refer to agricultural production rather than climate to define “normal” or “good” years in terms of rainfall.

Overall, East African farmers typically mention changes in timing of rainy seasons, including shift of onset and cessation dates, timing and magnitude of extreme events, including torrential rain and droughts rather than referring to rainfall amounts for describing experienced rainfall changes (Asfaw et al. 2018; Ayal and Leal Filho 2017; Cochrane et al. 2020; Debela et al. 2015; Habtemariam et al. 2016; Osbahr et al. 2011). Despite the importance of these indices the majority of studies that contrast perceptions with meteorological data utilizes rainfall amounts, mainly due to limited availability of reliable longitudinal daily rainfall data as well as conceptual challenges related to indices development (Asfaw et al. 2018; Esayas et al. 2019; Habtemariam et al. 2016). Studies that include dry spells (Adimassu et al. 2014), intensity of rainfall events or start of the seasons (Osbahr et al. 2011) in their analysis of meteorological data remain exceptions. Taken together, the existing research body provides valuable contributions to understanding long-term trends of rainfall amounts as both observed in meteorological data and perceived by rural farmers as well as possible discrepancies between both data sources. However, with the focus on rainfall amounts, existing research tends to neglect extreme events and, especially, changes in timing of rainfall seasons. Both can equally undermine rainfed agricultural production of subsistence farmers. This knowledge gap is particularly problematic given that variability of rainfall is expected to increase in East Africa and beyond (Dosio et al. 2021; Haile et al. 2020). Taken together, agreement and disagreement of climate change perceptions with meteorological data are not sufficiently understood, which limits the adaptive capacity of farmers to changes in rainfall pattern, including extreme events and hampers our understanding of farmers’ behavior.

Our study addresses this gap. As a case study, we selected South Wollo, located in the northern Ethiopian highlands because of its high climate variability together with a high vulnerability of rural farmers to climate change. We contrast rainfall changes as perceived by subsistence farmers with longitudinal meteorological daily rainfall data derived from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) covering the past nearly four decades. Specifically, we applied nine distinct metrics for rainfall dynamics, explicitly accounting for changes in timing of rainy seasons and extreme events. Thereby, we move beyond analyzing aggregated trends in rainfall amounts and pay particular attention to temporal metrics that are key for farmers' perceptions (Cochrane et al. 2020). The results will improve our understanding of the differences between measured and perceived rainfall changes to overcome barriers to successful climate change adaptation and to increase farmer resilience.

Study area South Wollo

We conducted this study in six kebeles (the smallest administrative unit of Ethiopia) in the South Wollo Zone in Amhara Regional State in the northern Ethiopian highlands (Fig. 1). The livelihoods of the local subsistence farmers in this region are characterized by a mix of livestock farming and rainfed agriculture (Little et al. 2006). Due to a growing population with increasingly fractionalized landholdings, fallow land is essentially non-existent and land scarcity has become a contentious issue for families and local communities (Ege 2017; Hermans and Garbe 2019; Morrissey 2013). In addition, the region is affected by severe land degradation, mainly in the form of top soil loss, gully erosion and declining soil fertility (Groth et al. 2020; Nyssen et al. 2004). Despite intense soil and water conservation efforts, soil fertility continues to decline and large areas in the Ethiopian highlands have become unsuitable for agriculture (Adimassu et al. 2017; Mekuriaw et al. 2018; Meshesha et al. 2014).

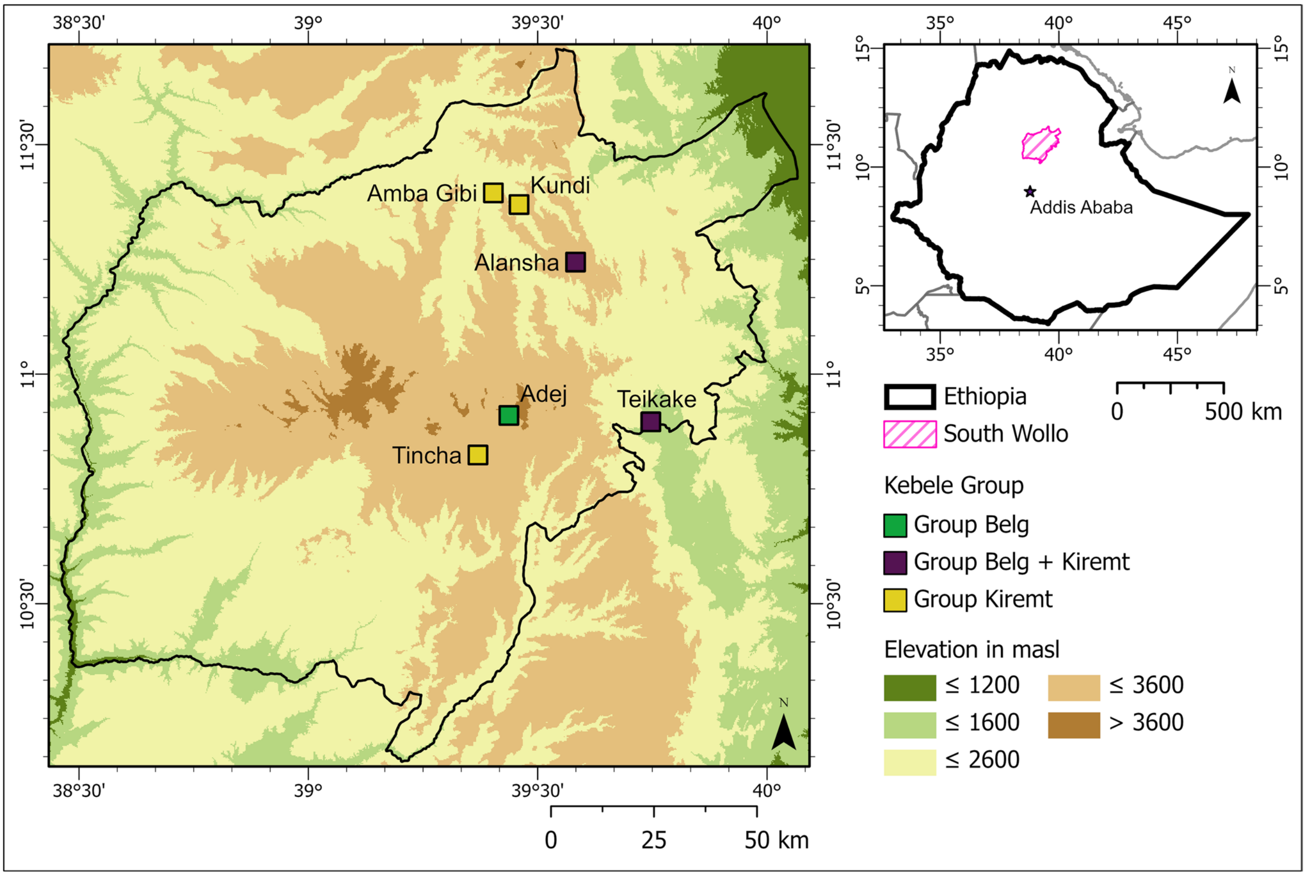

Fig. 1 Maps of South Wollo in Amhara Regional State in Ethiopia (right) and of the kebeles considered in our analysis, including elevation based on Farr et al. (2007) and administrative boundaries of South Wollo derived from OpenStreetMap contributors (left)

In South Wollo, rainfall is highly variable within and between years as well as across space (Alemu and Bawoke 2019; Mekonen and Berlie 2020). The rainfall regime is characterized by three distinct seasons: i) the short rainy season (belg) from February/March until May, ii) the long rainy season (kiremt) from late June to September/October, and iii) the dry season (bega) during the remaining months. It is particularly the belg season that is important for smallholders in South Wollo (Rosell 2011). In the high altitude areas of the highlands, farmers exclusively use the light belg rains as low temperatures, including frost, intense rainfall and hail during the kiremt season inhibit them from using the more abundant kiremt rains for agriculture (Groth et al. 2020; Hermans and Garbe 2019). Belg-dependent farmers are considered to be highly vulnerable to changes in rainfall conditions including extreme climate events such as droughts (Rosell and Holmer 2007).

Smallholder farmers in the Ethiopian highlands were found to perceive increasingly erratic and unpredictable rainfall, with delayed onset and earlier cessation of the rainy seasons, increasing rainfall intensity and an increasing occurrence of untimely rainfall and drought frequency (Ayal and Leal Filho 2017). However, existing rainfall analyses for the northern highlands have shown slightly diverging trends. While some scholars have identified temporal changes in rainfall amounts (Alemayehu and Bewket 2017; Mekonen and Berlie 2020) others found no significant changes (Alemu and Bawoke 2019; Ayalew et al. 2012; Mengistu et al. 2014). Besides, some studies show a delayed onset of belg (Rosell 2011) and an earlier cessation of kiremt (Ayalew et al. 2012), both leading to a shortening of the growing period. Temporal variability of rainfall was found to have increased by Rosell and Holmer (2007) while others describe temporal variation as high but largely stable, with belg showing larger variability than kiremt (Abtew et al. 2009; Rosell 2011). In addition, the mountainous terrain causes spatially highly variable rainfall patterns, which heavily influence local cropping activities.

Reasons for these differences between individual studies are manifold and include the (spatio-temporal) data resolution, the characteristics of the applied indices as well as the choice of observation periods (Bewket and Conway 2007).

Data

Meteorological rainfall data

CHIRPS is a quasi-global (50°N-50°S) precipitation dataset which blends the Climate Hazards Group's Precipitation Climatology (CHPclim) with satellite-based thermal infrared (TIR) precipitation estimates and gauge observations (Funk et al. 2015). In our analysis, we used daily rainfall amount data for the period 1981 through 2017 with a spatial resolution of 0.05° × 0.05°, which corresponds to approximately 5 km x 5 km in South Wollo.

CHIRPS has been validated over East Africa (Dinku et al. 2018; Gebrechorkos et al. 2018) and Ethiopia specifically (Ayehu et al. 2018; Bayissa et al. 2017) through comparison with gauge data. CHIRPS generally performed well in the validations compared to other satellite-based rainfall products. Specifically in the Ethiopian highlands, CHIRPS showed reliable performance at different elevations during the wet seasons. Compared to other satellite products Ayehu et al. (2018) and Dinku et al. (2018) evidenced that CHIRPS showed good to very good performance concerning bias by incorporating concurrent station observations for adjustment. The better performance of the CHIRPS data as compared to other satellite products makes them appropriate for various hydrological and rainfall analysis functions in complex topographic areas, such as conducted in our study (Ayehu et al. 2018; Dinku et al. 2018). Besides, the availability of a temporally and spatially complete dataset makes CHIRPS preferable for long-term analysis and facilitates the assessment of rainfall patterns at the local level. Using CHIRPS data allows us to overcome well-known limitations of satellite-based time series of climate change for comparing them with people's perceptions of climate change, such as limited temporal coverage, poor accuracy at higher temporal and spatial resolutions, and lacking homogeneity (Mekonnen et al. 2018).

Perceptions of rainfall changes

The data on perception of changes in rainfall variability used in this study are based on 42 semi-structured interviews (SSIs) and 18 focus group discussions (FGDs) with local officials and rural farmers, conducted between November 2017 and February 2018 by Groth et al. (2020) (Table 1). For the selection of the research sites, Groth et al. (2020) interviewed officials in 19 kebeles located within the four districts Legambo, Dese Zuria, Kutaber and Kalu to gain information on livelihoods, (rainfall-related) risks to these livelihoods and coping and adaptation strategies. Based on this information, the authors purposively sampled six kebeles across a gradient of agro-ecological conditions ranging from 1400 to 3600 masl (for details see Groth et al. 2020). The six kebeles are distinct with respect to their severity of land degradation, level of remoteness and the rainy seasons used for farming and consequently, adaptation and coping strategies. Given the importance of rainfed agriculture, farmers' perceptions of rainfall changes are likely to be affected by their agricultural activities (Cochrane et al. 2020), which, in turn, are influenced by the two rainy seasons. To account for this diversity, we grouped the six kebeles according to the prevailing rainy seasons: i) belg, ii) kiremt, iii) belg + kiremt (Fig. 1, Table 1). In group belg + kiremt, we looked at each season separately because the respondents used both seasons for their agricultural activities but distinguished between them during interviews and focus groups. The collection of perception data was done in Amharic with the help of a local assistant. The methods used during the focus groups included livelihood risk assessments and strategy ranking. In the household interviews, socio-economic characteristics, agricultural practices, perceived changes in rainfall and land degradation were assessed.

Table 1 Studied kebeles with corresponding cropping seasons, the number of focus group discussions and semi structured interviews

kebele	rainy season(s) used for cropping		perception data	
	belg	kiremt	focus groups	semi structured interviews
Adej	x		3	8
Alansha	x	x	3	6
Teikake	x	x	3	6
Amba Gibi		x	3	7
Kundi		x	3	7
Tincha		x	3	8
total	3	5	18	42

Methods

Analysis of rainfall measurements

For all grid cells located within the respective kebele we extracted the median CHIRPS value and used it as the precipitation estimate on a given day, resulting in a daily time series over the 37-year period of observation for each kebele. Following the Expert Team on Climate Change Detection and Indices (ETCCDI) recommendations for monitoring

Table 2 Description of the indices used for rainfall analysis with means and standard deviation by decade, separated by the kebele groups according to the rainy seasons used for agriculture

	1981–1990	1991–2000	2001–2010	2011–2017
RR	total seasonal rainfall in mm			
Belg	301.01 (80.84)	243.34 (88.12)	214.53 (67.69)	227.71 (59.14)
Belg + Kiremt (B)	323.56 (52.52)	262.39 (101.58)	236.23 (66.37)	260.12 (53.35)
Belg + Kiremt (K)	627.7 (174.87)	808.76 (156.81)	716.72 (85.46)	735.71 (194.64)
Kiremt	627.36 (172.47)	809.99 (159.28)	743.22 (101.24)	769.2 (204.63)
rd	number of rainy days (> 1 mm) in days			
Belg	22.4 (10.71)	15.3 (5.87)	14.1 (2.69)	17.29 (3.86)
Belg + Kiremt (B)	20.95 (7.6)	15.2 (5.75)	15.65 (2.86)	18.07 (1.54)
Belg + Kiremt (K)	35.55 (10.5)	43.6 (9.18)	42.05 (6.26)	45 (7.61)
Kiremt	41 (11.8)	45.7 (8.13)	44.13 (7.58)	46.86 (9.07)
ons	onset of the rainy season (> 15 mm over three consecutive days) in day of the year			
Belg	52 (13.7)	60.9 (18.77)	57.2 (12.88)	76.43 (15.31)
Belg + Kiremt (B)	49.65 (15.72)	58.7 (20.73)	57.65 (15.85)	71.64 (13)
Belg + Kiremt (K)	187.8 (11.13)	182 (11.9)	180.6 (10.5)	187.71 (8.57)
Kiremt	187.9 (10.17)	179.87 (13.46)	179.97 (10.34)	185.86 (8.49)
off	cessation of the rainy season (maximum seasonal cumulative anomaly) in day of the year			
Belg	111.6 (32.18)	115.2 (23.73)	102.7 (27.18)	116.29 (25.1)
Belg + Kiremt (B)	121.9 (22.79)	106.45 (30.83)	105.6 (21.55)	125.93 (20.92)
Belg + Kiremt (K)	239.2 (23.19)	253.35 (10.92)	248.8 (6.05)	257.93 (11.71)
Kiremt	235.87 (22.39)	249.47 (5.38)	247.53 (3.98)	251.48 (9.33)
dur	number of days between onset and cessation in days			
Belg	60.6 (29.79)	55.3 (32.49)	46.5 (31.48)	40.86 (29.66)
Belg + Kiremt (B)	73.25 (22.43)	48.75 (36.49)	48.95 (24.86)	55.29 (23.68)
Belg + Kiremt (K)	52.4 (25.67)	72.35 (8.57)	69.2 (14.09)	71.21 (12.54)
Kiremt	48.97 (24.38)	70.6 (11.21)	68.57 (12.68)	66.62 (12.67)
CDD	maximum number of consecutive dry days in days			
Belg	16.8 (9.3)	13.9 (7.46)	14.11 (8.25)	16.33 (8.57)
Belg + Kiremt (B)	18.9 (7.81)	19.25 (9.96)	12.95 (5.39)	17.29 (9.79)
Belg + Kiremt (K)	7.67 (4.9)	9.7 (4.94)	10.1 (8.87)	8.43 (4)
Kiremt	6.85 (2.09)	7.63 (4.05)	10.07 (6.25)	7.86 (4.05)
Rx1day	maximum 1-day precipitation in mm			
Belg	47.48 (22.57)	50.97 (12.89)	45.19 (20.55)	42.74 (16.03)
Belg + Kiremt (B)	47.63 (10.45)	50.26 (14.71)	40.55 (7.72)	45.01 (7.01)
Belg + Kiremt (K)	57.04 (11.27)	55.53 (9.55)	50.85 (10.14)	47.08 (15.19)
Kiremt	45.48 (9.65)	51.1 (4.54)	53.01 (9.06)	45.29 (11.59)
R95p	very wet days: percentage of wet days exceeding the 95th percentile of the period of observation in %			
Belg	7.08 (8.72)	7.12 (6.13)	4.7 (4.5)	4.6 (4.78)
Belg + Kiremt (B)	5.77 (5.85)	8.37 (8.39)	6.45 (5.35)	4.75 (2.47)
Belg + Kiremt (K)	8.44 (7.04)	5.78 (3.21)	4.17 (2.25)	3.56 (4.74)
Kiremt	5.11 (4.12)	7.09 (3.08)	5.12 (2.57)	3.09 (3.82)
SDII	simple daily intensity index: total seasonal precipitation divided by the number of wet days (> 1 mm) in mm/day			
Belg	15.96 (7.34)	16.16 (3.88)	15.02 (3.07)	13.5 (3.34)
Belg + Kiremt (B)	17.14 (4.94)	19.41 (8.24)	15.8 (3.62)	14.73 (3.25)
Belg + Kiremt (K)	18.68 (5.1)	18.72 (1.37)	17.19 (1.65)	16.27 (3.35)
Kiremt	16.07 (4.59)	17.75 (1.3)	17.06 (1.72)	16.42 (3.08)

rainfall change and extremes (Frich et al. 2002; Zhang et al. 2011) we analyzed rainfall trends and rainfall variability by means of nine indices (Table 2). We calculated the indices for each kebele and aggregated them for the three kebele groups.

In our study, we applied two definitions for a rainy season to account for the variety of rainfall dynamics and enable their calculations. First, a rainy season is defined as the time between the onset and cessation of the season according to the CHIRPS data. We used this data-driven definition to determine duration of the rainy seasons (dur) and the length of the longest dry spell of the season (CDD). Our second definition of a rainy season is based on local knowledge from the study region (Legese et al. 2018; Rosell 2011; Rosell and Holmer 2007). Accordingly, we define belg as the period from 1 February to 31 May, and kiremt as the period from 1 June to 31 October. We used this second definition to capture all rainfall events within these two periods, including days of scarce rainfall for which the calculation of onset and cessation based on the first definition was challenging due to extremely scarce rainfall in a given season. We applied this calendar-based definition to indices concerning rainfall amount, intensity and extreme events (RR, rd, Rx1day, R95p, SDII).

To determine rainy season onset, we used a threshold of at least 15 mm rainfall over three consecutive days. Hence, if over a period of 72 h at least 15 mm rainfall were accumulated the rainy season has started. This threshold was identified by Rosell (2011) based on traditional local knowledge of farmers from South Wollo and serves as a proxy for soil moisture, which is key for agricultural decision-making (Lala et al. 2020; MacLeod 2018). Considering that we aim to compare farmers' perceptions and meteorological rainfall data, using such a threshold-based onset definition that accounts for local agricultural practices of subsistence farmers is an appropriate way to derive a meaningful onset date.

To determine the cessation of the rainy seasons we used the method described by Liebmann and Marengo (2001), which has been successfully applied for onset and cessation determination in Africa (Liebmann et al. 2012). Since farmers are unlikely to plant outside the given time frame when rainfall usually occurs, we used the February through May period for belg and June through October period for kiremt to calculate cessation dates (Lala et al. 2020; MacLeod 2018). The assumption of the cessation determination is, that precipitation during a given rainy season exceeds its long-term average, in our case the 37 year average (Dunning et al. 2016; Liebmann and Marengo 2001). Hence, the cessation day is defined as the day of the year when the daily cumulative rainfall anomaly is at its absolute maximum, as following that day, rainfall is less than the 37 year average (Liebmann et al. 2012).

Further, we follow the recommendations of the ETCCDI to enhance comparability of climate change studies and included the following indices in our analyses of rainfall changes: total rainfall amount (RR), number of rainy days (rd), maximum 1-day precipitation (Rx1day), percentage of very wet days (R95p) and the simple daily intensity index (SDII) (Table 2). Analyzing extreme events is particularly relevant in the context of our study since they have been found to shape perceptions significantly (Debela et al. 2015).

To assess change in temporal rainfall variability, we aggregated the daily results to four periods (1981–1990, 1991–2000, 2001–2010 and 2011–2017), for each we calculated the mean value ($\bar{x}$), standard deviation (σ) and coefficient of variation (CV). CV is calculated as the division of the standard deviation by the mean value. Since CV requires ratio scaled data, it was not calculated for rainy season onset and cessation.

Additionally, we performed the non-parametric Mann–Kendall (MK) trend test (Kendall 1975; Mann 1945) and calculated Sen's Slope estimator (Sen 1968) to detect trends and magnitude of potential rainfall changes. Before performing trend analysis, we inspected the data for possible autocorrelations, none of which were found. The rainfall analysis was implemented in R (R Core Team 2020). All calculations for the MK trend test were performed using the *Kendall* package (McLeod 2011). Kendall's rank correlation coefficient (tau) was calculated to assess the direction of trends and a two-sided p-value was used to test for statistical significance. We calculated Sen's slope estimator at the 95% confidence interval (CI) using the *trend* package (Pohlert 2020) to assess the average change per year.

Analysis of perception data

During the semi-structured household interviews, Groth et al. (2020) asked farmers about observed changes in rainfall, their impacts and the strategies to deal with these changes. Additionally, during the FGDs farmers were asked to outline livelihood related trends within the last 20 years, where rainfall was a relevant issue. In the context of risk and strategy ranking, farmers also commented on rainfall related questions.

To ensure consistency and to facilitate the comparison between perceived and measured rainfall data, we developed a framework similar to Simelton et al. (2013) to organize and contrast the two different data sources (Fig. 2). As a first step, we assessed whether respondents had perceived changes in rainfall or not. The responses were then categorized according to the rainy season they used for their agricultural activities. In the next step, we categorized the interview data according to rainfall changes as perceived by the farmers. This included dry spells, extreme events such as torrential rainfall and timing of the rainy seasons. In the last step, we assessed how the rainfall had changed according to the respondents in terms of rainfall amount, its

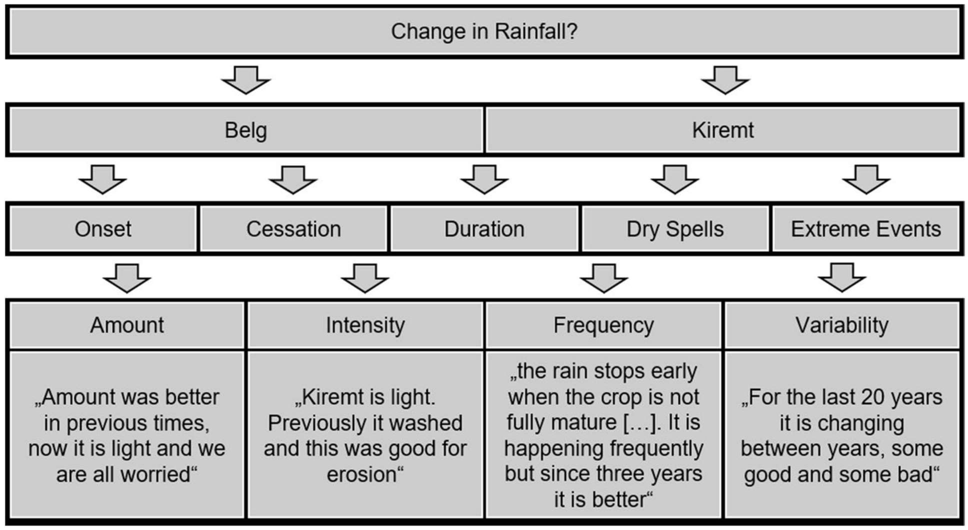

Fig. 2 Categorization of perceptions of rainfall changes from qualitative data, including example quotes from subsistence farmers (Groth et al. 2020). Modified from Simelton et al. (2013)

intensity, the frequency of changes occurring and whether the rain has become more or less variable over the years. We considered information potentially affecting agricultural production, such as land degradation, frost or weed infestation and adaptation strategies to contextualize the perception data. The interview analysis was performed in MAXQDA (VERBI Software 2019).

Results

Group belg

Results of the CHIRPS analysis for group belg show that rainfall amounts during belg have decreased significantly between 1981 and 2017 with Sen's slope estimator indicating an average annual decrease of 2.7 mm (Table 3). Variability of rainfall amounts peaked in the 1990s (CV 0.36) and has continually fallen in the subsequent decades. This high rainfall variability results from drought occurrences during belg seasons in this decade. Additionally, belg is starting significantly later: while belg used to start on the 52nd day of the year (21-Feb) in the 1980s, the onset moved to the 76th day of the year (17-Mar) in the 2010s (Fig. 3). Timing of rainfall has consistently been highly variable with standard deviations between 13 and 19 days for rainy season onset and 24 to 27 days for cessation. While rainy season duration has shortened (although not significantly at the 95% CI), standard deviations for rainfall duration have remained stable resulting in increasing CV throughout the period of observation. As compared to the 1980s, the occurrence of

Table 3 Results of the Mann Kendall trend test and Sen's Slope estimator, significant trends at 95% CI are bold

	ons	off	dur	CDD	RR	rd	Rx1day	R95p	SDII
Group belg									
tau	**0.2736**	-0.0136	-0.2121	-0.065	**-0.2462**	-0.1249	-0.027	-0.0592	-0.036
p	**0.0185**	0.9166	0.0688	0.5983	**0.033**	0.2934	0.824	0.6349	0.7636
Sens slope	**0.6883**	-0.0623	-0.7454	-0.0625	**-2.6589**	-0.0801	-0.0741	0	-0.0264
Group belg + kiremt (B)									
tau	**0.2805**	0.003	-0.1687	-0.0903	-0.2222	-0.064	-0.1081	0.0046	-0.1141
p	**0.0155**	0.9896	0.1464	0.4594	0.0545	0.5911	0.3531	0.9791	0.3266
Sens slope	**0.5526**	0	-0.767	-0.0952	-2.349	-0.0359	-0.1647	0	-0.0675
Group belg + kiremt (K)									
tau	-0.0182	0.2071	0.1873	0.0258	0.2012	**0.2384**	-0.2222	**-0.2926**	-0.2162
p	0.8855	0.075	0.1074	0.8378	0.0819	**0.041**	0.0545	**0.0115**	0.0614
Sens slope	-0.0109	0.2857	0.3964	0	4.4125	**0.2981**	-0.3576	**-0.1429**	-0.0829
Group kiremt									
tau	-0.0935	0.2155	0.2078	0.066	**0.2643**	0.0995	0.0871	-0.0918	-0.042
p	0.4247	0.0632	0.0731	0.585	**0.0221**	0.395	0.456	0.4325	0.724
Sens slope	-0.0976	0.2546	0.4452	0.0303	**6.1692**	0.135	0.1243	-0.0423	-0.0106

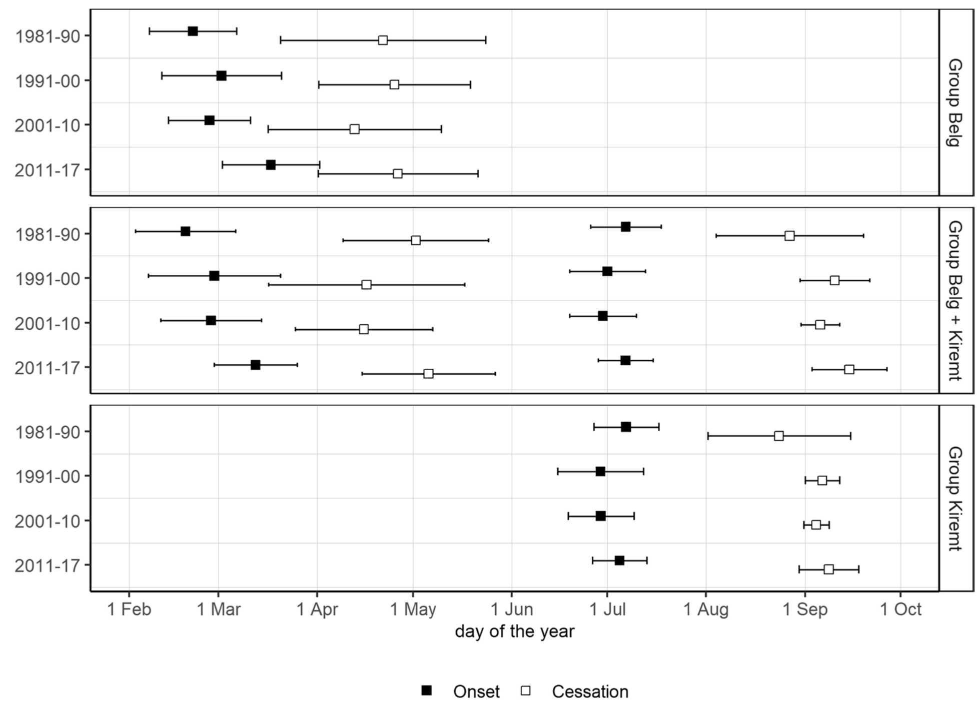

Fig. 3 Onset and cessation per rainy season by decade. Note: the squares present the onset and cessation; the horizontal bars indicate the standard deviation

extreme events (R95p) was less variable in the 1990s but have become more variable in recent decades (Fig. S5).

Farmer's perceptions of changes in rainfall largely correspond with these measured changes. Respondents are mainly concerned about the timing of the rain, in particular its onset: it is perceived as being delayed and increasingly unpredictable. Respondents view the uncertainty of belg as the biggest risk to their livelihood and are particularly concerned about it. According to the farmers, the increasingly later onset of belg delays the growing period resulting in the crops being immature by the time the strong kiremt rains start. At the high-altitude locations with steep slopes, kiremt rains can lead to crop loss through soil erosion or hail, which urges farmers to harvest their crops before kiremt starts. The increased variability of belg duration according to the CHIRPS analysis coincides with the increasing uncertainty of belg as perceived by farmers.

> *"When belg is late we lose our harvest. In 2008 we lost food and fodder. I sold sheep and goats to sustain the family. I worked in a government program and after that the government filled the six months gap."* – local farmer from Adej. The respondent refers to the Ethiopian calendar when mentioning the year 2008, which corresponds with 2015 in the Gregorian calendar

Group belg + kiremt

Similar to the belg group, the onset of belg in this kebele group has moved significantly later in the year (Table 3): while belg rains started on average on Feb 19 in the 1980s, it is on Mar 13 in the 2010s (Fig. 3). The 1990s were an exceptionally dry decade for belg resulting in more variable rainfall, hence, higher CV values. All belg indices in group belg + kiremt reached their highest CVs and standard deviations in the 1990s and variability has declined since then with the exception of CDD who's variability has increased again in the 2010s (Fig. S5). Overall, belg in group belg + kiremt is starting later and has become less variable since the 1990s according to the CHIRPS data, which is in contrast to the development in the belg group.

Kiremt rainfall has experienced a significant increase in the number of rainy days (rd) with Sen's slope estimator indicating an average annual increase of 0.3 days (Table 3). Hence, the rainy season got longer. Extreme rainfall events and intensity indices during kiremt all decreased between 1981 and 2017. However, only for very wet days (R95p), the decrease is significant at the 95% CI while decrease in maximum daily precipitation (Rx1day) and intensity (SDII) are not significant (Table 3). Rainfall amount (RR) and the number of rainy days (rd) were becoming less variable between the 1980s and 2000s, but recently increased in variability. Similarly, the variability of the duration of kiremt was at CV = 49% in the 1980s and between CV = 12–20% in the following decades (Fig. S5). Except for the 1980s, the timing of kiremt can be described as largely stable (Fig. 3). Extreme events and intensity indices were more variable in the 1980s than in the following decades but experienced increasing variability again in the 2010s (Fig. S5).

Similar to what we observed in group belg farmers in group belg + kiremt are concerned about the onset of belg and its increasing uncertainty. Farmers perceive an increasingly delayed onset. Further, farmers indicated that it has become increasingly difficult to know when the rain starts. Belg amounts are perceived to have declined during the past four decades. Respondents largely agree on declining rainfall amounts, less intense rainfall and higher variability during belg. In contrast, perceptions of changes in kiremt are much more heterogeneous and not all interviewees perceive changes in kiremt rains (Fig. 4). Those who do are especially concerned with the timing of the rain and mention delayed onset and earlier cessation of the rain. Decreasing amounts of kiremt rain is only mentioned by few respondents, while others negate decreasing amounts. Heavy rainfall events during kiremt are not seen as a major problem, although some mention it to be increasing. According to those farmers, heavy rainfall sometimes produces gullies, destroys terraces and leads to water logging and flooded fields. The perceived increase in extreme events may be expressed in the increasing variability of these rainfall indices.

> *"Belg is light at these times. It stops early but I can use irrigation. Without irrigation it would be a problem. Before we had irrigation, the soil contained more water and even with little belg we had a harvest."*
> *"The amount of kiremt is declining, but there is no impact for us. The springs have vanished in our vil-*

		Rainfall Analysis	Farmers' Perception
Belg	Trend	amount ↘ | onset ↗	amount ↘ | onset ↗
	Var	amount ↘ | duration ↗ extreme event frequency ↗	onset ↗
Belg + Kiremt (B)	Trend	onset ↗	amount ↘ | onset ↗ | duration ↘ | intensity ↘
	Var	amount ↘ | rainy days ↘ | onset ↘ | cessation ↘ duration ↘ | intensity ↘ extreme event frequency ↘ | extreme event intensity ↘	amount ↗ | onset ↗
Belg + Kiremt (K)	Trend	rainy days ↗ | extreme event frequency ↘	onset ↗ | cessation ↘ | extreme event frequency ↗
	Var	onset ↘ | intensity ↗ extreme event intensity ↗	
Kiremt	Trend	amount ↗	amount ↘ | onset ↗ | cessation ↘ | duration ↘
	Var	onset ↘ | duration ↗ | intensity ↗ extreme event frequency ↗ extreme event intensity ↗	amount ↗ | onset ↗ | cessation ↗

↗ = increasing trend/variability (for onset/cessation: date later in the year)
↘ = decreasing trend/variability (for onset/cessation: date earlier in the year)

Fig. 4 Comparison of rainfall changes according to the meteorological data and farmers perceptions. Rainfall indices with a significant trend at the 95% CI are shown as increasing/decreasing in the trend row (Trend). Rainfall indices with consistently increasing/decreasing CV (or σ for onset and cessation) since 1991 are shown in the variability row (Var). Farmers' perceptions of change are indicated when respondents largely agreed on dynamics

lage, but it is no problem for our family because we use the river to water the cattle and have a water pipe."
- local farmers from Teikake
"There is no problem with kiremt. Only sometimes heavy rainfall produces a gully next to my house. I fear that it will affect my house, the electric pillar may fall down."
- local farmer from Alansha

Other than in the belg-dependent group, some farmers have access to irrigation systems which improves their water availability. This allows farmers to harvest twice a year, after each rainy season, and provides more certainty for farmers who sow in belg and harvest after kiremt. For farmers without access to irrigation, changes in belg are seen as one of the biggest livelihood threats and was reported to be the main reason for declining agricultural yields. Farmers with access to irrigation, especially from the lowest-altitude locations, stressed that farming during the belg season would not be possible without additional irrigation. In line with farmers from group belg, respondents stress the adverse impacts of the shortened growing period on the crop production: the delayed start of the belg rain causes crops being immature by the time the more abundant and partly destructive kiremt rains start. As a result, yields are lower than expected or immature crops are used for fodder, meaning food crops need to be purchased.

Group kiremt

The MK test results for group kiremt show a statistically significant increase in total kiremt rainfall amounts with Sen's slope estimator indicating an average annual increase of 6.2 mm (Table 3). CV of rainfall amounts and rainy days decreased until the 2000s and increased again in the 2010s (Fig. S5). The decrease in CV till the 2000s results from the 1980s droughts.

Variability of the maximum dry spell length increased since the 1980s. The variability of rainy season onset has decreased consistently since the 1990s from $\sigma = 13.5$ to $\sigma = 8.5$ days. With $\sigma = 22.4$ days for rainy season cessation in the 1980s, the droughts of that decade are most visible. Variability of cessation has been far lower in the following decades with $\sigma = 5.4$ and $\sigma = 4$ days but experienced an increase again in the 2010s with $\sigma = 9.3$ days (Fig. 3). This may be due to the drought in 2015 and the fact that the 2010s period includes fewer datapoints than the three periods before. Extreme events and intensity became less variable in the 1990s than they were in the 1980s, but have been increasing in variability since, replicating the familiar CV development of group belg + kiremt (Fig. S5).

In line with the records for the two other groups, respondents in this group most frequently mention concerns regarding the timing of rainfall, hence, duration, onset and cessation of kiremt. They mention delayed onsets, increasing unpredictability and especially earlier cessation of the rain as a major problem. When being asked about changes in rainfall, farmers often do not distinguish between changes in timing and changes in amounts of rain, hence, shorter rainy seasons are often perceived as providing less rainfall amounts. The respondents' perception is not in line with the results from the meteorological rainfall analysis (Fig. 4). The severe drought during kiremt in 2015 may have influenced this perception, however, the two years between the drought in 2015 and data collection in 2017 were some of the wettest years in the period of observation according to the CHIRPS data.

"In previous times there was good rain, it started in June or July and lasted until September. We had a good harvest. But nowadays it starts in July and stops in August and the crop is not fully matured."
"The crops don't grow well and the harvest is not enough for the whole year, if the rain starts late and wheat and teff are planted in July. When the rain stops in August it is not a good harvest."
"My father used to say the rain comes from June to October. At this time, it starts in mid-July and ends by the end of August. The scarcity of rain increases our poverty year by year. I started with producing Araki but with good yield I would not do this."
- local farmers from Amba Gibi

The perceived shorter rainy seasons, in particular the earlier cessation, lead to shorter growing periods according to farmers, which causes immaturity of the crops at the end of the season and a decline in yields. Respondents mention increasing food insecurity as a consequence. Often, the immature crops are used as fodder and food crops need to be purchased. Since a delayed onset of the rain means delayed sowing, many respondents have problems with their immature crops being affected by frost in October/November. Early cessation of the rain is often mentioned as a problem in combination with fertilizer usage, as the fertilizer leads to crop burn in case of a lacking rainfall.

Discussion

Changes in water availability and adaptation strategies

Overall, interviewed farmers perceived increasingly unreliable rainfall, with delayed onset and earlier cessation of the rainy seasons, increasing rainfall intensity and an increasing occurrence of untimely rainfall and drought frequency, which confirms earlier findings for the study region from Ayal and Leal Filho (2017). Most respondents view these changes in rainfall as a direct cause for changes in agricultural yield: good rainfall translates into high yields and poor rainfall into low yields.

Hence, adverse developments of rainfall patterns are perceived as the primary cause of decreasing agricultural yields. This was true for respondents in all three kebele groups and confirms previous observations that farmers perceive changes in rainfall primarily in how it affects their cropping activities, for example for identifying the optimal planting date (Ayal and Leal Filho 2017; Mekonnen et al. 2018; Rosell and Holmer 2007).

However, the CHIRPS rainfall data show most significant changes in rainfall only in the high-altitude belg-dependent kebeles. Since the early 1980s belg-dependent kebeles have been experiencing decreasing rainfall amounts, with high variability between years, as well as a nearly one-month delayed start of the rainy season, which, above all, is characterized by an increasing uncertainty. In contrast, kebeles using kiremt rain (exclusively or in addition to belg) experienced little change in rainfall amounts and variability during the overall period of observation and are characterized by rather stable rainfall conditions. However, disaggregated per decade it becomes apparent that after the 1980s, with comparable little kiremt rainfall amounts, the variability of extreme rainfall events, in terms of both intensity and frequency, has increased since the 1990s.

Discrepancies between measured and perceived rainfall change in East Africa, including Ethiopia, have been described by Adimassu et al. (2014) and Osbahr et al. (2011). The authors conclude that such discrepancies may result from factors influencing water availability and agricultural production, such as increasing water demand due to population growth, land degradation, increasing temperatures and evapotranspiration as well as the use of different crops and crop varieties as farmers closely link rainfall to their agricultural output. Together, this points towards changing water availability and water needs as a possible explanation for the perceived deteriorating rainfall conditions.

Belg-dependent farmers in the study area are highly dependent on livestock sale to generate income in case of a failed harvest with few alternative strategies available (Hermans and Garbe 2019). In contrast, farmers belonging to the group belg + kiremt, who perceived their quality of life as better overall, usually have more strategies available to compensate a lost harvest. Furthermore, our results show that these farmers have access to irrigation. Irrigation access increases their water availability and, hence, reduces their dependency on rainfall, which has been proven to shape perceptions of rainfall change (Niles and Mueller 2016).

The role of land degradation

Climatic changes, such as analyzed in our study, can have direct and indirect effects on land degradation, including changes in soil moisture availability, increases in soil erosion by wind and rain, soil nutrient loss, and an overall decline in vegetation and biomass (Olsson et al. 2019). In our study, some respondents mentioned the impacts of heavy rainfall events have become more severe in recent years, and thus exacerbated land degradation, for example through gully formation, top soil erosion and seeds being washed away. Besides climate change intensive agricultural production and land mismanagement are major causes for the severe degradation of the Ethiopian highlands, which constitute a global hotspot of land degradation, including deforestation (Groth et al. 2021; Nyssen et al. 2004; Piontek et al. 2014). Despite the vast occurrence of various forms of land degradation and its impact on agricultural productivity respondents were more likely to blame changing rainfall patterns rather than land degradation as the more severe threat to their livelihood.

Identifying and investigating soil conditions was beyond the scope of our study. However, it is remarkable that two out of the three kebeles that exclusively use kiremt rains were identified as areas with high land degradation in the site selection process (Groth et al. 2020). In these kebeles, the discrepancy between perceived and measured rainfall change was the largest amongst all kebeles. The specific linkages between climate change, extreme events like droughts and torrential rainfall, land degradation and risk perceptions of affected populations are typically complex and subject of multi-scale interactions of environmental and non-environmental processes (Hermans and McLeman 2021; Olsson et al. 2019). Further, narratives about changing rainfall in local communities can manifest potentially inaccurate perceptions of climate change. Media, (international) aid organizations, extension workers and political institutions active in the region focus strongly on extreme climate events, such as abnormal rainfall and extraordinary drought. Together, this can significantly shape risk perceptions of climate change (Carlton et al. 2016; Meze-Hausken 2004). As rainfall is largely seen as something that cannot be influenced locally, it is easier to point to it as the cause of various agricultural problems rather than addressing highly conflict prone issues such as land degradation or land scarcity (Ege 2017). Taken together, this led us conclude that the role of land degradation in shaping farmer's perception of rainfall change requires further investigation.

Methodological reflection

Comparing data on one specific subject, here climate change, that have inherently different characteristics poses some major challenges.

To start with, given the inherent subjectivity of the responses they can only to some extent directly be compared amongst each other. One reason is that not all respondents sufficiently separated between phenomena in the same way they were treated in the remote sensing-based rainfall analysis. This can, for example, mean that a shorter rainy season was equated with less rain. As a result, changes in rainfall as perceived by local farmers may be covered by different indices in the meteorological analysis.

Similarly, the perception of decreased rainfall amounts may not be confirmed by meteorological data (Fig. 4). However, discrepancies between observed and perceived climate changes does not necessarily indicate errors in the measurements, nor do they imply that perceptions are wrong per se. Rather, they hint at the fact that farmers observe changes according to their water needs, in terms of both timing and amount for agricultural production. These water demands may not be sufficiently reflected in aggregated measures of rainfall trends, such as changes in monthly rainfall amounts or duration of rainy seasons (without consideration of the rainfall period). Rather, using high-resolution data for analyzing climate changes, as well as accounting for the timing and intensity of extreme events, or shifts in the rainy seasons is key for understanding the challenges farmers face when experiencing climate variability (Cochrane et al. 2020). Together, this stresses the importance of appropriate climate reference scales used by farmers and through meteorological analysis (Debela et al. 2015; Howe et al. 2014). Further, we found that changes in rainfall variability was conceptually difficult to understand for many rural subsistence farmers. Responses referring to increasing uncertainty of rainfall cover a variety of processes, including increasing fluctuation of "good" and "bad" years or decreasing predictability of rainy seasons, which we coded as such. This confirms the findings of Madhuri and Sharma (2020) and stresses the need for a sufficiently detailed explanation of terminology, as well as their consistent use (Dickinson et al. 2017; Mekonnen et al. 2018), to allow for a robust collection of perception data. Besides terminology, Kosmowski et al. (2016) emphasize the importance of language for correctly capturing perceptions of climate change. This is especially relevant for situations where the local languages diverge from the scientific description of climate parameters under study, which challenges a common understanding of these processes.

In our study we used retrospective data on rainfall change perceptions. Such data have their flaws as people can remember long-term climate trends to a limited extent only. Besides, the severe ENSO-related drought during kiremt in 2015 may have influenced the perception in the belg-dependent kebeles since extreme and more recent events have been shown to be extraordinarily relevant in shaping people's perception of environmental change (Debela et al. 2015; Simelton et al. 2013). Alternatively, collecting longitudinal perception data could improve the robustness of comparisons between measured and perceived changes in climate over a longer period. This way, the influence of extreme events on risk perceptions of climate change could more appropriately be accounted for. The above discussion illustrates that perceptions of people and meteorological observations may be measuring different things. While objectively measured data capture the characteristics of rainfall, local knowledge of farmers incorporates variables affecting water availability and agricultural productivity beyond rainfall. With our results we confirm the findings of Dickinson et al. (2017), who conclude that using perceptions and meteorological data complementarily is more meaningful for understanding climate change and its impacts than identifying the most accurate data source. By reviewing meteorological observations, local decision-makers can identify areas affected by adverse rainfall change. Combining meteorological information with local knowledge about rainfall patterns and agricultural conditions can serve an important additional data source for farmers, decision-makers and scientists. It can improve our understanding of rainfall in regions with sparse station coverage and take additional important factors such as water availability and soil conditions into account.

Finally, the determination of the timing of the rainy seasons according to the objective measurements proved challenging in the study area. This was particularly relevant for the lighter belg rains as the unreliability of the rain in some years complicated the determination of onset and cessation of the rainy season. This may have led to the data-driven rainy season definition to determine very short rainy seasons although more rain may have been available later in the season. To account for uncertainties with respect to the start and end of a rainy season we additionally used the calendar-based rainy season definition. Such an approach is probably not necessarily needed for situations where rainfall seasons are more pronounced than in our case study.

Further, the choice of observation period was found to be particularly decisive for rainfall analyses outcomes due to the 1980s being an exceptionally dry and the 1990s an exceptionally wet decade for kiremt (Bewket and Conway 2007). Taken together, indices using the data-driven rainy season definition should be interpreted carefully.

Conclusions

Our analysis shows that rainfall amounts and patterns in South Wollo have changed during the past nearly four decades. Overall, this was confirmed by both meteorological observations as well as perceptions of rural subsistence farmers. Yet, different trends between the two rainy seasons are noticeable and discrepancies exist to some extent between measurements and perceptions.

The CHIRPS data most notably illustrate decreasing rainfall amounts with increasing interannual variability and a significant delayed start of the rainy season for the belg season, which was confirmed by the farmers themselves. In contrast, kiremt farmers generally perceive more changes than the measured rainfall data shows. Other than for belg, for kiremt the CHIRPS data show comparably little changes in rainfall amounts and variability during the 37-year period of observation. This discrepancy may be a result of public discourse, methodological issues in the rainfall analysis or the role of factors other than rainfall change that leads to decreases in agricultural output, such as land degradation.

Taken together, they can shape farmers perceptions of changing environmental conditions.

Overall, farmers using both rainy seasons seem to be the most resilient. Reasons for this are manifold and include land degradation being considered less severe than in all other kebeles. Furthermore, farmers living in kebeles with both belg and kiremt rainfall available for agriculture have some limited access to irrigation, which leads to a more optimistic perception of rainfall change and their economic situation. Together, this shows the importance to analyze rainfall changes locally and seasonally as they are mainly perceived in how they affect agricultural activities. More attention should be paid to meteorological indices covering rainfall timing and intensities—rather than merely trends in rainfall amounts – as these have a direct impact on farmers' cropping activities. Ultimately, this will help to better understand the impact on farmers and can improve their adaptive capacity.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-023-02064-9.

Acknowledgement LH, JG, and KH acknowledge funding from the German Federal Ministry of Education and Research (BMBF) within the Junior Research Group MigSoKo (01UU1606). The research reported in this paper contributes to the Programme on Ecosystem Change and Society (http://www.pecsscience. org/).

We especially thank Mr. Tegegne Ali for facilitating the data collection in Ethiopia. Furthermore, we thank all involved farmers and interviewees for the valuable information and their patience. We thank the two anonymous reviewers for their valuable feedback to improve the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data Availability CHIRPS precipitation data is available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/. Access to the interview data is available from the first author upon reasonable request.

References

Abtew W, Melesse AM, Dessalegne T (2009) Spatial, inter and intra-annual variability of the Upper Blue Nile Basin rainfall. Hydrol Process 23:3075–3082. https://doi.org/10.1002/hyp.7419

Adger WN, Dessai S, Goulden M, Hulme M, Lorenzoni I, Nelson DR, Naess LO, Wolf J, Wreford A (2009) Are there social limits to adaptation to climate change? Clim Change 93:335–354. https://doi.org/10.1007/s10584-008-9520-z

Adimassu Z, Kessler A, Stroosnijder L (2014) Farmers′ strategies to perceived trends of rainfall and crop productivity in the Central Rift Valley of Ethiopia. Environ Dev 11:123–140. https://doi.org/10.1016/j.envdev.2014.04.004

Adimassu Z, Langan S, Johnston R, Mekuria W, Amede T (2017) Impacts of soil and water conservation practices on crop yield, run-off, soil loss and nutrient loss in Ethiopia: Review and synthesis. Environ Manage 59:87–101. https://doi.org/10.1007/s00267-016-0776-1

Alemayehu A, Bewket W (2017) Local spatiotemporal variability and trends in rainfall and temperature in the central highlands of Ethiopia. Geografiska Annaler: Series A, Physical Geography 99:85–101. https://doi.org/10.1080/04353676.2017.1289460

Alemu MM, Bawoke GT (2020) Analysis of spatial variability and temporal trends of rainfall in Amhara region, Ethiopia. J Water Clim Change 11:1505–1520. https://doi.org/10.2166/wcc.2019.084

Alessa L, Kliskey A, Williams P, Barton M (2008) Perception of change in freshwater in remote resource-dependent Arctic communities. Glob Environ Change 18:153–164. https://doi.org/10.1016/j.gloenvcha.2007.05.007

Allen MR, Dube OP, Solecki W, Aragón-Durand F, Cramer W, Humphreys S, Kainuma M, Kala J, Mahowald N, Mulugetta Y, Perez R, Wairiu M, Zickfeld K (2018) Framing and context. In: Masson-Delmotte V, Zhai VP, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, JBR M, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In Press

Asfaw A, Simane B, Hassen A, Bantider A (2018) Variability and time series trend analysis of rainfall and temperature in north-central Ethiopia: A case study in Woleka sub-basin. Weather Clim Extremes 19:29–41. https://doi.org/10.1016/j.wace.2017.12.002

Ayal DY, Leal Filho W (2017) Farmers' perceptions of climate variability and its adverse impacts on crop and livestock production in Ethiopia. J Arid Environ 140:20–28. https://doi.org/10.1016/j.jaridenv.2017.01.007

Ayalew D, Tesfaye K, Mamo G, Yitaferu B, Bayu W (2012) Variability of rainfall and its current trend in Amhara region, Ethiopia. Afr J Agric Res 7:1475–1486. https://doi.org/10.5897/AJAR11.698

Ayehu GT, Tadesse T, Gessesse B, Dinku T (2018) Validation of new satellite rainfall products over the Upper Blue Nile Basin, Ethiopia. Atmos Meas Tech 11:1921–1936. https://doi.org/10.5194/amt-11-1921-2018

Bayissa Y, Tadesse T, Demisse G, Shiferaw A (2017) Evaluation of Satellite-Based Rainfall Estimates and Application to Monitor Meteorological Drought for the Upper Blue Nile Basin, Ethiopia. Remote Sensing 9:669. https://doi.org/10.3390/rs9070669

Bewket W, Conway D (2007) A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. Int J Climatol. 27:1467–1477. https://doi.org/10.1002/joc.1481

Carlton JS, Mase AS, Knutson CL, Lemos MC, Haigh T, Todey DP, Prokopy LS (2016) The effects of extreme drought on climate change beliefs, risk perceptions, and adaptation attitudes. Clim Change 135:211–226. https://doi.org/10.1007/s10584-015-1561-5

Cochrane L, Lewis SC, Engdaw MM, Thornton A, Welbourne DJ (2020) Using farmer-based metrics to analyze the amount, seasonality, variability and spatial patterns of rainfall amidst climate

change in southern Ethiopia. J Arid Environ 175:104084. https://doi.org/10.1016/j.jaridenv.2019.104084
Debela N, Mohammed C, Bridle K, Corkrey R, McNeil D (2015) Perception of climate change and its impact by smallholders in pastoral/agropastoral systems of Borana. South Ethiopia. Springerplus 4:236. https://doi.org/10.1186/s40064-015-1012-9
Dickinson KL, Monaghan AJ, Rivera IJ, Hu L, Kanyomse E, Alirigia R, Adoctor J, Kaspar RE, Oduro AR, Wiedinmyer C (2017) Changing weather and climate in Northern Ghana: comparison of local perceptions with meteorological and land cover data. Reg Environ Change 17:915–928. https://doi.org/10.1007/s10113-016-1082-4
Dinku T, Funk C, Peterson P, Maidment R, Tadesse T, Gadain H, Ceccato P (2018) Validation of the CHIRPS satellite rainfall estimates over eastern Africa. Q J R Meteorol Soc 144:292–312. https://doi.org/10.1002/qj.3244
Dosio A, Jury MW, Almazroui M, Ashfaq M, Diallo I, Engelbrecht FA, Klutse NAB, Lennard C, Pinto I, Sylla MB, Tamoffo AT (2021) Projected future daily characteristics of African precipitation based on global (CMIP5, CMIP6) and regional (CORDEX, CORDEX-CORE) climate models. Clim Dyn 57:3135–3158. https://doi.org/10.1007/s00382-021-05859-w
Dunning CM, Black ECL, Allan RP (2016) The onset and cessation of seasonal rainfall over Africa. J Geophys Res Atmos 121:11405–11424. https://doi.org/10.1002/2016JD025428
Ege S (2017) Land tenure insecurity in post-certification Amhara, Ethiopia. Land Use Policy 64:56–63. https://doi.org/10.1016/j.landusepol.2017.02.015
Esayas B, Simane B, Teferi E, Ongoma V, Tefera N (2019) Climate Variability and Farmers' Perception in Southern Ethiopia. Adv Meteorol 2019:7341465. https://doi.org/10.1155/2019/7341465
Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L, Seal D, Shaffer S, Shimada J, Umland J, Werner M, Oskin M, Burbank D, Alsdorf D (2007) The shuttle radar topography mission. Rev Geophys. 45:RG2004. https://doi.org/10.1029/2005RG000183
Fosu-Mensah BY, Vlek PLG, MacCarthy DS (2012) Farmers' perception and adaptation to climate change: a case study of Sekyedumase district in Ghana. Environ Dev Sustain 14:495–505. https://doi.org/10.1007/s10668-012-9339-7
Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank AM, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. Clim Res 19:193–212. https://doi.org/10.3354/cr019193
Funk C, Peterson P, Landsfeld M, Pedreros D, Verdin J, Shukla S, Husak G, Rowland J, Harrison L, Hoell A, Michaelsen J (2015) The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci Data 2:150066. https://doi.org/10.1038/sdata.2015.66
Gebrechorkos SH, Hülsmann S, Bernhofer C (2018) Evaluation of multiple climate data sources for managing environmental resources in East Africa. Hydrol Earth Syst Sci 22:4547–4564. https://doi.org/10.5194/hess-22-4547-2018
Groth J, Ide T, Sakdapolrak P, Kassa E, Hermans K (2020) Deciphering interwoven drivers of environment-related migration – A multisite case study from the Ethiopian highlands. Glob Environ Change 63:102094. https://doi.org/10.1016/j.gloenvcha.2020.102094
Groth J, Hermans K, Wiederkehr C, Kassa E, Thober J (2021) Investigating environment-related migration processes in Ethiopia – A participatory Bayesian network. Ecosystems and People 17:128–147. https://doi.org/10.1080/26395916.2021.1895888
Habtemariam LT, Gandorfer M, Kassa GA, Heissenhuber A (2016) Factors influencing smallholder farmers' climate change perceptions: A study from farmers in Ethiopia. Environ Manage 58:343–358. https://doi.org/10.1007/s00267-016-0708-0
Haile GG, Tang Q, Hosseini-Moghari S-M, Liu X, Gebremicael TG, Leng G, Kebede A, Xu X, Yun X (2020) Projected impacts of climate change on drought patterns over East Africa. Earth's Future 8:e2020EF001502. https://doi.org/10.1029/2020EF001502
Hermans K, Garbe L (2019) Droughts, livelihoods, and human migration in northern Ethiopia. Reg Environ Change 19:1101–1111. https://doi.org/10.1007/s10113-019-01473-z
Hermans K, McLeman R (2021) Climate change, drought, land degradation and migration: exploring the linkages. Curr Opin Environ Sustain 50:236–244. https://doi.org/10.1016/j.cosust.2021.04.013
Howe PD, Thaker J, Leiserowitz A (2014) Public perceptions of rainfall change in India. Clim Change 127:211–225. https://doi.org/10.1007/s10584-014-1245-6
IPCC (2022) Climate change 2022. In: Impacts adaptation and vulnerability contribution of Working Group II to the sixth assessment report of the intergovernmental panel on climate change, Cambridge
Juana JS, Kahaka Z, Okurut FN (2013) Farmers' perceptions and adaptations to climate change in Sub-Sahara Africa: A synthesis of empirical studies and implications for public policy in African agriculture. JAS 5:121–135. https://doi.org/10.5539/jas.v5n4p121
Kendall MG (1975) Rank correlation methods, 4th edn. Charles Griffin, London
Kosmowski F, Leblois A, Sultan B (2016) Perceptions of recent rainfall changes in Niger: a comparison between climate-sensitive and non-climate sensitive households. Clim Change 135:227–241. https://doi.org/10.1007/s10584-015-1562-4
Lala J, Tilahun S, Block P (2020) Predicting rainy season onset in the Ethiopian highlands for agricultural planning. J Hydrometeorol 21:1675–1688. https://doi.org/10.1175/JHM-D-20-0058.s1
Legese W, Koricha D, Ture K (2018) Characteristics of seasonal rainfall and its distribution over bale highland, Southeastern Ethiopia. J Earth Sci Clim Change 9:10000443. https://doi.org/10.4172/2157-7617.1000443
Liebmann B, Marengo JA (2001) Interannual variability of the rainy season and rainfall in the Brazilian Amazon Basin. J Clim 14:4308–4318. https://doi.org/10.1175/1520-0442(2001)014<4308:IVOTRS>2.0.CO;2
Liebmann B, Bladé I, Kiladis GN, LMV C, Senay GB, Allured D, Leroux S, Funk C (2012) Seasonality of African precipitation from 1996 to 2009. J Clim 25:4304–4322. https://doi.org/10.1175/JCLI-D-11-00157.1
Little PD, Stone MP, Mogues T, Castro AP, Negatu W (2006) 'Moving in place': Drought and poverty dynamics in South Wollo, Ethiopia. J Dev Stud 42:200–225. https://doi.org/10.1080/00220380500405287
MacLeod D (2018) Seasonal predictability of onset and cessation of the east African rains. Weather Clim Extremes 21:27–35. https://doi.org/10.1016/j.wace.2018.05.003
Madhuri SU (2020) How do farmers perceive climate change? A systematic review. Clim Change 162:991–1010. https://doi.org/10.1007/s10584-020-02814-2
Mann HB (1945) Nonparametric tests against trend. Econometrica 13:245–259. https://doi.org/10.2307/1907187
McLeod AI (2011) Package 'Kendall'. Kendall rank correlation and Mann-Kendall trend test. https://cran.r-project.org/web/packages/Kendall/Kendall.pdf. Accessed 10 Nov 2020
Mekonen AA, Berlie AB (2020) Spatiotemporal variability and trends of rainfall and temperature in the Northeastern Highlands of Ethiopia model. Earth Syst. Environ 6:285–300. https://doi.org/10.1007/s40808-019-00678-9
Mekonnen Z, Kassa H, Woldeamanuel T, Asfaw Z (2018) Analysis of observed and perceived climate change and variability in Arsi Negele District, Ethiopia. Environ Dev Sustain 20:1191–1212. https://doi.org/10.1007/s10668-017-9934-8

Mekuriaw A, Heinimann A, Zeleke G, Hurni H (2018) Factors influencing the adoption of physical soil and water conservation practices in the Ethiopian highlands. Int Soil Water Conserv Res 6:23–30. https://doi.org/10.1016/j.iswcr.2017.12.006

Mengistu D, Bewket W, Lal R (2014) Recent spatiotemporal temperature and rainfall variability and trends over the Upper Blue Nile River Basin, Ethiopia. Int J Climatol 34:2278–2292. https://doi.org/10.1002/joc.3837

Meshesha DT, Tsunekawa A, Tsubo M, Ali SA, Haregeweyn N (2014) Land-use change and its socio-environmental impact in Eastern Ethiopia's highland. Reg Environ Change 14:757–768. https://doi.org/10.1007/s10113-013-0535-2

Meze-Hausken E (2004) Contrasting climate variability and meteorological drought with perceived drought and climate change in northern Ethiopia. Clim Res. 27:19–31. https://doi.org/10.3354/cr027019

Morrissey JW (2013) Understanding the relationship between environmental change and migration: The development of an effects framework based on the case of northern Ethiopia. Glob Environ Change 23:1501–1510. https://doi.org/10.1016/j.gloenvcha.2013.07.021

Niles MT, Mueller ND (2016) Farmer perceptions of climate change: Associations with observed temperature and precipitation trends, irrigation, and climate beliefs. Glob Environ Change 39:133–142. https://doi.org/10.1016/j.gloenvcha.2016.05.002

Nyssen J, Poesen J, Moeyersons J, Deckers J, Haile M, Lang A (2004) Human impact on the environment in the Ethiopian and Eritrean highlands—a state of the art. Earth-Sci Rev 64:273–320. https://doi.org/10.1016/S0012-8252(03)00078-3

Olsson L, Barbosa H, Bhadwal S, Cowie A, Delusca K, Flores-Renteria D, Hermans K, Jobbagy E, Kurz W, Li D, Sonwa DJ, Stringer L (2019) Land degradation. In: Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J (eds.)]. In Press

Osbahr H, Dorward P, Stern R, Cooper S (2011) Supporting agricultural innovation in Uganda to respond to climate risk: linking climate change and variability with farmer perceptions. Ex Agric. 47:293–316. https://doi.org/10.1017/S0014479710000785

Piontek F, Müller C, Pugh TAM, Clark DB, Deryng D, Elliott J, Colón González FJ, Flörke M, Folberth C, Franssen W, Frieler K, Friend AD, Gosling SN, Hemming D, Khabarov N, Kim H, Lomas MR, Masaki Y, Mengel M et al (2014) Multisectoral climate impact hotspots in a warming world. Proc Natl Acad Sci U S A 111:3233–3238. https://doi.org/10.1073/pnas.1222471110

Pohlert T (2020) Package 'trend'. Non-parametric trend tests and change point detection. https://cran.r-project.org/web/packages/trend/trend.pdf.

R Core Team (2020) R. A language for statistical computing. R Foundation for Statistical Computing, Vienna https://www.r-project.org/.

Rosell S (2011) Regional perspective on rainfall change and variability in the central highlands of Ethiopia, 1978–2007. Appl Geogr 31:329–338. https://doi.org/10.1016/j.apgeog.2010.07.005

Rosell S, Holmer B (2007) Rainfall change and its implications for Belg harvest in South Wollo, Ethiopia. Geografiska Annaler: Series A, Physical Geography 89:287–299. https://doi.org/10.1111/j.1468-0459.2007.00327.x

Sen FK (1968) Estimates of the regression coefficient based on Kendall's Tau. J Am Stat Assoc 63:1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Simelton E, Quinn CH, Batisani N, Dougill AJ, Dyer JC, Fraser ED, Mkwambisi D, Sallu S, Stringer LC (2013) Is rainfall really changing? Farmers' perceptions, meteorological data, and policy implications. Clim Dev 5:123–138. https://doi.org/10.1080/17565529.2012.751893

Tessema YA, Aweke CS, Endris GS (2013) Understanding the process of adaptation to climate change by small-holder farmers: the case of East Hararghe Zone, Ethiopia. Agric Econ 1:13. https://doi.org/10.1186/2193-7532-1-13

Thompson HE, Berrang-Ford L, Ford JD (2010) climate change and food security in Sub-Saharan Africa: a systematic literature review. Sustainability 2:2719–2733. https://doi.org/10.3390/su2082719

VERBI Software (2019) MAXQDA. VERBI Software, Berlin https://www.maxqda.com/

Zhang X, Alexander L, Hegerl GC, Jones P, Tank AK, Peterson TC, Trewin B, Zwiers FW (2011) Indices for monitoring changes in extremes based on daily temperature and precipitation data. WIREs Clim Change 2:851–870. https://doi.org/10.1002/wcc.147