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Is wetter better? Exploring agriculturally-relevant rainfall characteristics over four decades in the Sahel

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Abstract

The semi-arid Sahel is a global hotspot for poverty and malnutrition. Rainfed agriculture is the main source of food and income, making the well-being of rural population highly sensitive to rainfall variability. Studies have reported an upward trend in annual precipitation in the Sahel since the drought of the 1970s and early '80s, yet farmers have questioned improvements in conditions for agriculture, suggesting that intraseasonal dynamics play a crucial role. Using high-resolution daily precipitation data spanning 1981–2017 and focusing on agriculturally-relevant areas of the Sahel, we re-examined the extent of rainfall increase and investigated whether the increases have been accompanied by changes in two aspects of intraseasonal variability that have relevance for agriculture: rainy season duration and occurrence of prolonged dry spells during vulnerable crop growth stages. We found that annual rainfall increased across 56% of the region, but remained largely the same elsewhere. Rainy season duration increased almost exclusively in areas with upward trends in annual precipitation (23% of them). Association between annual rain and dry spell occurrence was less clear: increasing and decreasing frequencies of *false starts* (dry spells after first rains) and *post-floral dry spells* (towards the end of the season) were found to almost equal extent both in areas with positive and those with no significant trend in annual precipitation. Overall, improvements in at least two of the three intraseasonal variables (and no declines in any) were found in 10% of the region, while over a half of the area experienced declines in at least one intraseasonal variable, or no improvement in any. We conclude that rainfall conditions for agriculture have improved overall only in scattered areas across the Sahel since the 1980s, and increased annual rainfall is only weakly, if at all, associated with changes in the agriculturally-relevant intraseasonal rainfall characteristics.

1. Introduction

The drought-prone Sahelian belt in Sub-Saharan Africa is among the poorest regions in the world [1]. Food and income security of its growing rural population rely largely on small-scale rainfed agriculture. Precipitation—through its strong correlation with soil moisture—is a key limiting factor to agricultural productivity in the region's semi-arid climate [2–4]. Understanding its variability and change is therefore critical for the success of agriculture and thus the livelihoods of the population.

The Sahel experienced an extremely dry period during the 1970s and 1980s [5], causing widespread famine and malnutrition. Since the mid-1980s, various sources have reported at least a partial recovery towards wetter conditions in terms of annual precipitation (P_a) [6–8], which has been credited for the observed greening of the Sahel [9–11]. This implies that hydroclimatic conditions

for vegetation—natural and cultivated—may have improved since the drought years.

However, the Sahel's greening seems to be strongly related to woody vegetation, and impacts for herbaceous vegetation are not as clear [12–14]. Farmers in the region have also questioned the potential improvement towards more favourable vegetation and crop conditions, and have instead highlighted that seasonal characteristics of rainfall have changed in ways that may not only be positive [15]. For instance, in Burkina Faso, farmers across study sites agreed that farming activities are difficult to plan, as the onset and cessation of the rainy season have become less predictable [16]. These notions emphasise the need to look beyond cumulative annual and seasonal rainfall, and also address intraseasonal rainfall dynamics.

Studies have generally found increased rainfall variability within the growing season in the Sahel during the past decades. This is manifested particularly in mean intensity of daily precipitation [17, 18] and number of wet days [6], which are considered the main contributors to the upward trends in P_a. Previous research has also found increased probability of extreme daily rainfall [19, 20], with extreme events also becoming even more extreme [21].

The flipside of increased seasonal variability—intermittent lack of rain—has received considerably less attention, despite its importance for water-limited agriculture. Lack of rain can be expressed, e.g. as prolonged dry spells during the rainy season and decrease in season length. These periods without rain have been shown to lead to crop water stress and productivity declines [22–24]. The few regional studies on these rainfall characteristics have reached somewhat different conclusions about recent trends and their potential implications for agriculture. For instance, while the observed shortening of average dry spell length implies a positive change [6], prolonged dry spells during sensitive crop growth stages still appear to persist [25]. These results are not entirely comparable, however, because of differences in dry spell definitions, study area, and resolution of the analyses. Length of the rainy season (LRS) has been found to both increase [26, 27] and exhibit no trend over the past few decades [18], but these findings, too, are limited in their spatial coverage and resolution.

Thus, with inconclusive results and methodological limitations of previous studies, the nature and extent of recent decades' rainfall deficits remain unresolved. To fill this gap, we investigate here whether the widely reported wetting of the Sahel has led to positive change in selected agriculturally-relevant rainfall characteristics. We examine two aspects of intraseasonal rainfall variability that limit water availability for crops and are known to impact yields and agricultural management strategies: (a) the LRS and (b) the occurrence of prolonged dry spells during vulnerable crop growth stages; specifically '*false starts*'

(FS) around the beginning of the rainy season and '*post-floral dry spells*' (PFDS) towards the end of the season. For this investigation, we use a recently published, high-resolution precipitation dataset, focusing on trends in intraseasonal rainfall variables over 1981–2017 and their association with P_a.

2. Data and methods

2.1. Defining the study region
We define the Sahel as the region between $10°$ and $20°$ N and spanning across the African continent, where mean P_a during 1981–2017, according to the CHIRPS data ([28], see below), is between 100 mm and 600 mm. Within this region, there is a steep latitudinal gradient both in terms of P_a and LRS (supplementary figure S1 (available online at stacks.iop.org/ERL/16/035002/mmedia)). The rainy season starts to build up around May and tails off by October, with most of the annual rain falling between June and September.

Since our focus is on agriculturally-relevant rainfall characteristics, we further limit the study area to a sub-region within the Sahel, where certain minimum hydroclimatic conditions for agriculture are met. We consider the minimum P_a that can sustain rainfed agriculture to be 300 mm, assuming cultivation of millet, which has the lowest water requirement of staple crops widely cultivated in the region [29]. Additionally, we consider the minimum LRS (see below) to be 60 d. Some of the early-maturing varieties of millet take about 55–65 d to mature [30, 31]. This definition thus assumes sowing of an early-maturing millet variety right after the start of the season. The analysis focuses on a narrow strip in southern Sahel where we consider agriculture to be viable, as these two conditions are met $\geqslant 70\%$ of the years (figure S1).

2.2. Data
For rainfall data, we used the quasi-global precipitation dataset CHIRPS at $0.05°$ resolution and daily time step over the years 1981–2017 [28]. CHIRPS is based on the mean monthly precipitation climatology CHPclim [32], remotely sensed thermal infrared data, and gauge station data. We chose the CHIRPS data because of its high enough temporal and spatial resolution and relatively long time series that covers the 1980s, which is considered to mark the end of the drought decades before rainfall started to recover [5]. CHIRPS has been shown to generally agree on the sign of trends in intraseasonal rainfall variables, but overestimate positive trends in the number of wet days in West African Sahel [6]. Therefore, it is reasonable to assume that our results on improvements (declines) in intraseasonal variables are somewhat optimistic (conservative), at least in the western part of the study area.

Table 1. Definitions of terms and indices used in the paper.

Term	Definition (unit)
Dry day	Day with accumulated rainfall <1 mm according to the CHIRPS data
Dry spell	Two or more consecutive dry days
First rains	The first day of a rain event occurring after 15 April, during which rainfall accumulated over three consecutive days is at least 20 mm
Start date of the rainy season (D_{onset})	The first day of a rain event occurring after 15 April, during which rainfall accumulated over three consecutive days is at least 20 mm and no dry spell of $\geqslant$7 d occurs during the following 20 d
End date of the rainy season (D_{end})	The first day from 1 September after which there are 21 or more consecutive days with 7 d rainfall sums below 4 mm
LRS	D_{end} minus D_{onset} (days)
FS	A dry spell of $\geqslant$7 d occurring during the 20 d following first rains, i.e. first rains $\neq D_{onset}$
PFDS	A dry spell of $\geqslant$10 d occurring between 50 d after D_{onset} and D_{end}.

2.3. Calculation of length of the rainy season

The rainy season in the Sahel is relatively short and its timing and length varies between seasons. This variability means that in some years, crops may not have time to reach maturity before the end of rains, which may lead to yield reduction or even total crop failure. We define the onset of the rainy season (D_{onset}) as the first day after 15 April when rainfall accumulated over three consecutive days is at least 20 mm ('first rains') and no dry spell of $\geqslant$7 d occurs during the following 20 d (see table 1 for dry spell definitions) [33]. End of the rainy season (D_{end}) is defined as the first day from 1 September after which there are 21 or more consecutive days with 7 d rainfall rolling sums below 4 mm (i.e. 50% of the minimum weekly crop-water requirement of 8 mm [34]). LRS (expressed as number of days) was calculated as D_{end} minus D_{onset}. When D_{onset} could not be defined (no major rain events without a 7 d dry spell during the following 20 d), LRS was considered to be 0.

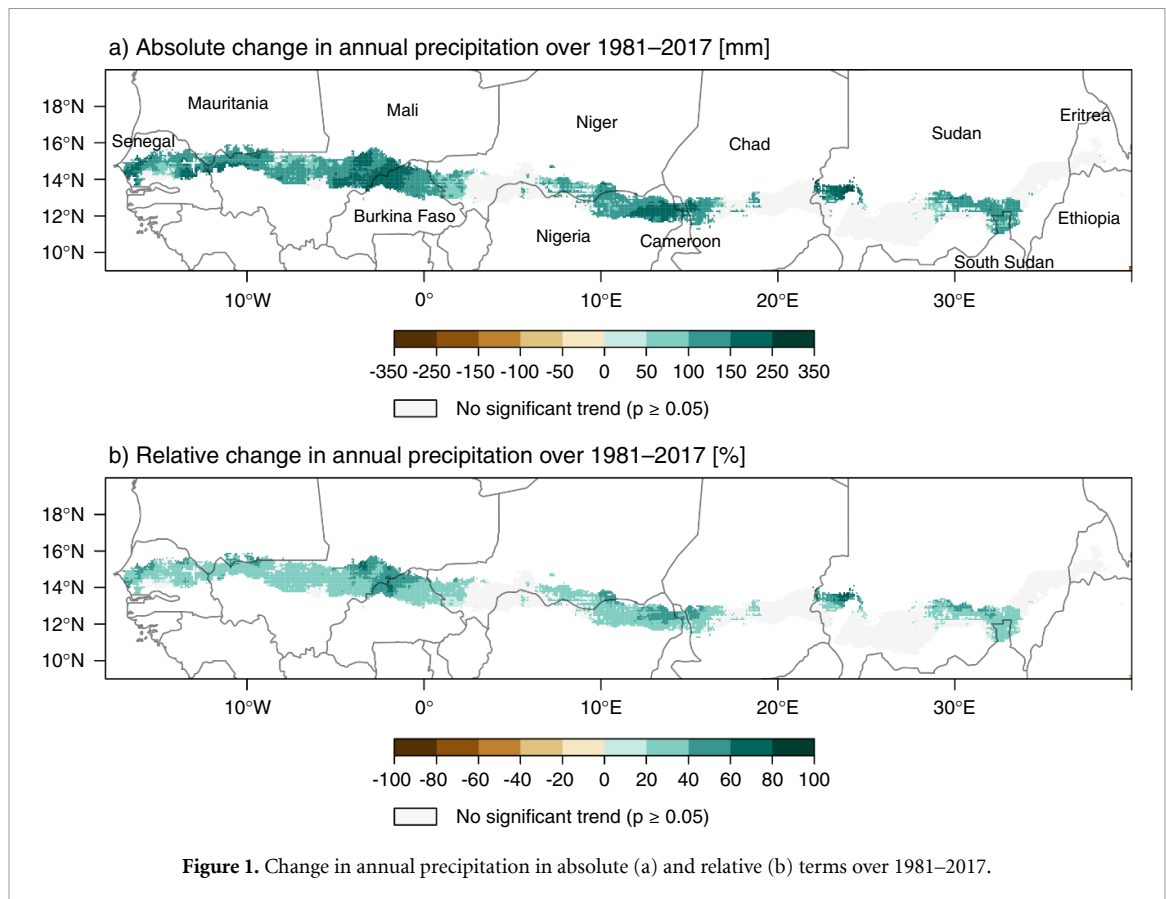## 2.4. Dry spell definitions

Precipitation anomalies correlate strongly with soil moisture across the Sahel [3, 4]. Prolonged dry spells are thus likely to lead to crop water stress [22, 35]. Millet and sorghum, the two main staple crops grown in the Sahel, are, like other cereals, particularly sensitive to water stress during the first month after sowing and during the flowering and grain filling stages [23–25, 36]. We explored the occurrence of dry spells, i.e. consecutive days with rainfall <1 mm d^{-1}, during these two sensitive periods. We considered dry spells of $\geqslant$7 d during the 20 d from the first rains (see table 1) as FS of the rainy season. These short dry spells after sowing may prevent the germination or emergence of plants and can lead to the necessity of resowing or to complete crop failure if farmers do not have the means to do so [34]. Even with resowing or a later first sowing date, yield reductions are likely due to loss of growing days and missing of the nitrogen flush that is available through mineralization

following the first rains [24]. Cases where the criteria for first rains were not met were considered to experience a FS.

Highest yield reductions are associated with dry spells occurring during the flowering and grain filling stages, i.e. towards the end of the growing season [36, 37]. Following Salack *et al* [25], we defined this sensitive post-floral period as starting from 50 d after D_{onset} and lasting until D_{end}. We refer to dry spells of 10 d or longer during this period as PFDS. In reality, the timing of flowering and grain filling stages would naturally depend on a variety of other factors than just time since D_{onset}, such as farmers' sowing strategy and the crop variety and its photoperiod-sensitivity (e.g. non photoperiod-sensitive millet and sorghum varieties' maturing times can range from 70 to 120 d while photoperiod-sensitive varieties' crop cycle is largely determined by day length [37]). Cases where LRS was 0 were considered to experience a PFDS.

2.5. Trend analyses

Presence of trends in P_a and LRS was assessed with the nonparametric Spearman's correlation coefficient, with time (years 1981–2017) as the explanatory variable (i.e. trends did not have to be linear), and *p*-values computed via the asymptotic *t* approximation. The same method was applied for trends in frequency of PFDS and FS, except occurrence (% of years) over 10 year moving windows was used as the dependent variable and the 10 year moving windows as the explanatory variable. For statistically significant trends ($p < 0.05$), the rate of change over the study period (37 years for P_a and LRS, 28 for the moving windows approach) was calculated using a linear regression model. Statistically significant but weak trends (rate of change <10% for P_a, 10 d for LRS and 20 pp for PFDS and FS) were not considered when presenting the results.

Figure 1. Change in annual precipitation in absolute (a) and relative (b) terms over 1981–2017.

3. Results

3.1. Trends in annual precipitation and intraseasonal variables

P_a increased significantly in about 56% of the study area during 1981–2017. Large areas without any detectable significant trend were found in parts of Niger, Nigeria, Chad, Sudan and Eritrea (figure 1). Highest absolute increases were found in northern Burkina Faso, northern Nigeria and mountainous regions of Sudan, where P_a increased by over 200 mm over 1981–2017. The same regions stand out in relative terms too, with a considerable 40%–60% increase in P_a, or even a 60%–80% increase in some smaller patches in Mali, Burkina Faso and Sudan.
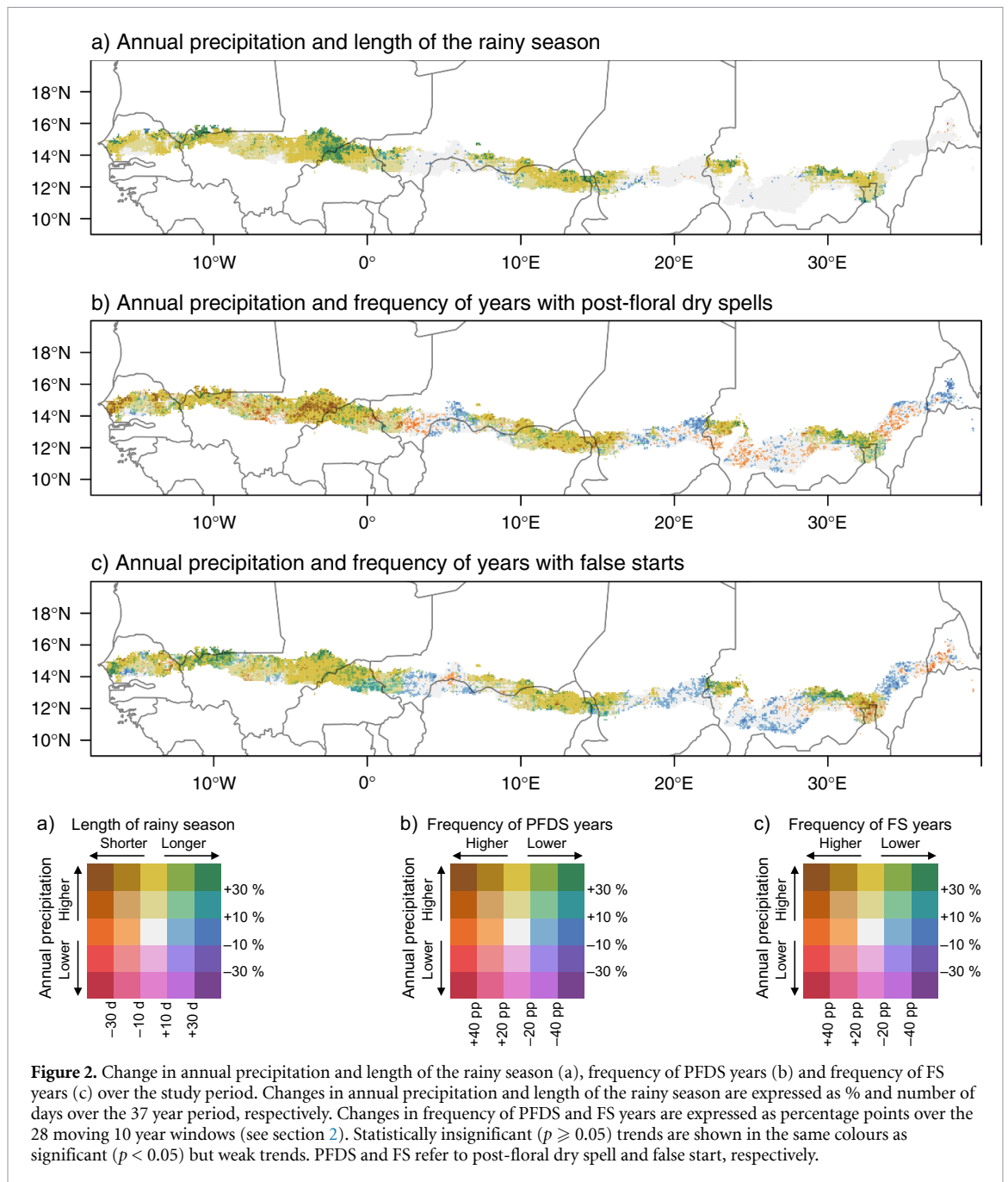
Trends in LRS followed those in P_a to some extent (green and turquoise patches in figure 2(a)), but for most areas with increased P_a, more rain did not result in longer rainy seasons (yellow in figure 2(a), supplementary table S1). On the other hand, increases in LRS were found almost exclusively in areas with upward trends in P_a, most of them located in western parts of the study region.

Increasing, decreasing and constant frequency of FS and PFDS were found to almost equal extent both in areas with increasing P_a and those with no significant trend (table S1). In western Sahel, increasing frequency of PFDS (brown and orange in figure 2(b)) was, in fact, much more common than

decreasing frequency (green, turquoise and blue), despite the generally strong positive trends in P_a. Overall, decreasing frequency of PFDS was slightly more common in regions where P_a did not increase (blue in figure 2(b)) than in those with increasing P_a (green and turquoise), suggesting that absence of dry spells was often not a result of a higher P_a.

Decreasing frequency of FS (green, turquoise and blue in figure 2(c)) was much more common than increasing frequency (brown and orange), but as with LRS and PFDS, no significant trend could be detected in a majority of the study region, regardless of whether P_a increased or not (table S1). In addition, we found contrasting shifts in FS and PFDS frequency trends—for example, in a number of regions, such as parts of Senegal, Niger, Sudan and Eritrea, increasing PFDS co-occurred with decreasing FS or vice versa (figures 2(b) and (c)).

Overall, improvements in terms of at least one of the examined hydroclimatic variables were found in 75% of the region, covering areas along the whole Sahelian band (table 2, figure 3(a)). However, in 15% of the area, mostly located in western Sahel, improvements were accompanied by declines in at least one of the variables. In 25% of the region, most of which is located in Sudan, Eritrea, Chad and Niger, improvements were not found for any of the variables, with some variables even exhibiting declines. Improvements in at least two, and no declines in any, of the variables were found in 27% of the region

Figure 2. Change in annual precipitation and length of the rainy season (a), frequency of PFDS years (b) and frequency of FS years (c) over the study period. Changes in annual precipitation and length of the rainy season are expressed as % and number of days over the 37 year period, respectively. Changes in frequency of PFDS and FS years are expressed as percentage points over the 28 moving 10 year windows (see section 2). Statistically insignificant ($p \geqslant 0.05$) trends are shown in the same colours as significant ($p < 0.05$) but weak trends. PFDS and FS refer to post-floral dry spell and false start, respectively.

(7% and 1% for improvements in three and four variables, respectively).

When considering only the intraseasonal variables (LRS, PFDS and FS, figure 3(b)), the pattern changes quite drastically, suggesting that it was largely driven by improvements in P_a. Only 48% of the region improved in terms of at least one intraseasonal variable (but 8% of that area also exhibited declining trends in at least one variable), and 52% saw no improvements and/or experienced declines (table 2, figure 3(b)). Changes are notable particularly in parts of Senegal, Mali and Nigeria, which did not improve and/or declined in terms of intraseasonal variables despite improvements in P_a. Burkina Faso, on the other hand, stands out as having mostly improved, even when only intraseasonal variables

are considered. About 10% of the region experienced improvements in at least two intraseasonal variables and no decline in the third, while only 1% experienced improvements in all three intraseasonal variables.

3.2. Interannual variability of rainfall
In addition to trends in rainfall characteristics, we examined how interannual variability of P_a was reflected in the intraseasonal variables. Higher (lower) than average P_a did, in general, increase the possibility of a higher (lower) than median LRS (figure 4(a)), but there was significant spatial variation: P_a and LRS correlated only in some parts of the region (Spearman's $\rho > 0.6$, $p < 0.05$, $n = 37$ for each grid cell), often with positive trends in both P_a and

Figure 3. Regions that experienced improvements without declines (i.e. improvement in at least one variable, no declines in any), no improvements (i.e. no trend and/or declines) or mixed trends with both improvements and declines among all (including P_a) (a) and only intraseasonal (LRS, PFDS and FS) (b) rainfall variables.
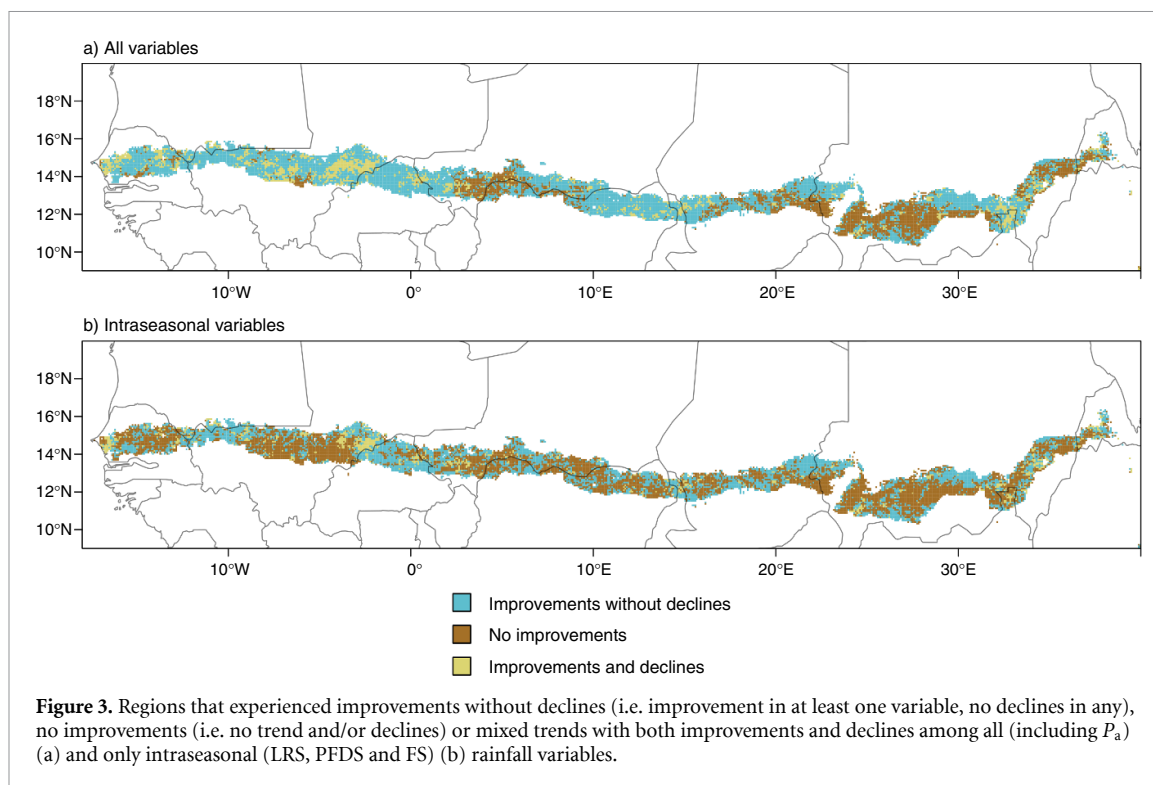
Table 2. Percentage of area with improvements (in at least one variable, no decline in others), no improvements or only declines, or mixed trends (both improvements and declines) among all (including annual precipitation P_a) or only intraseasonal variables (LRS, FS and PFDS).

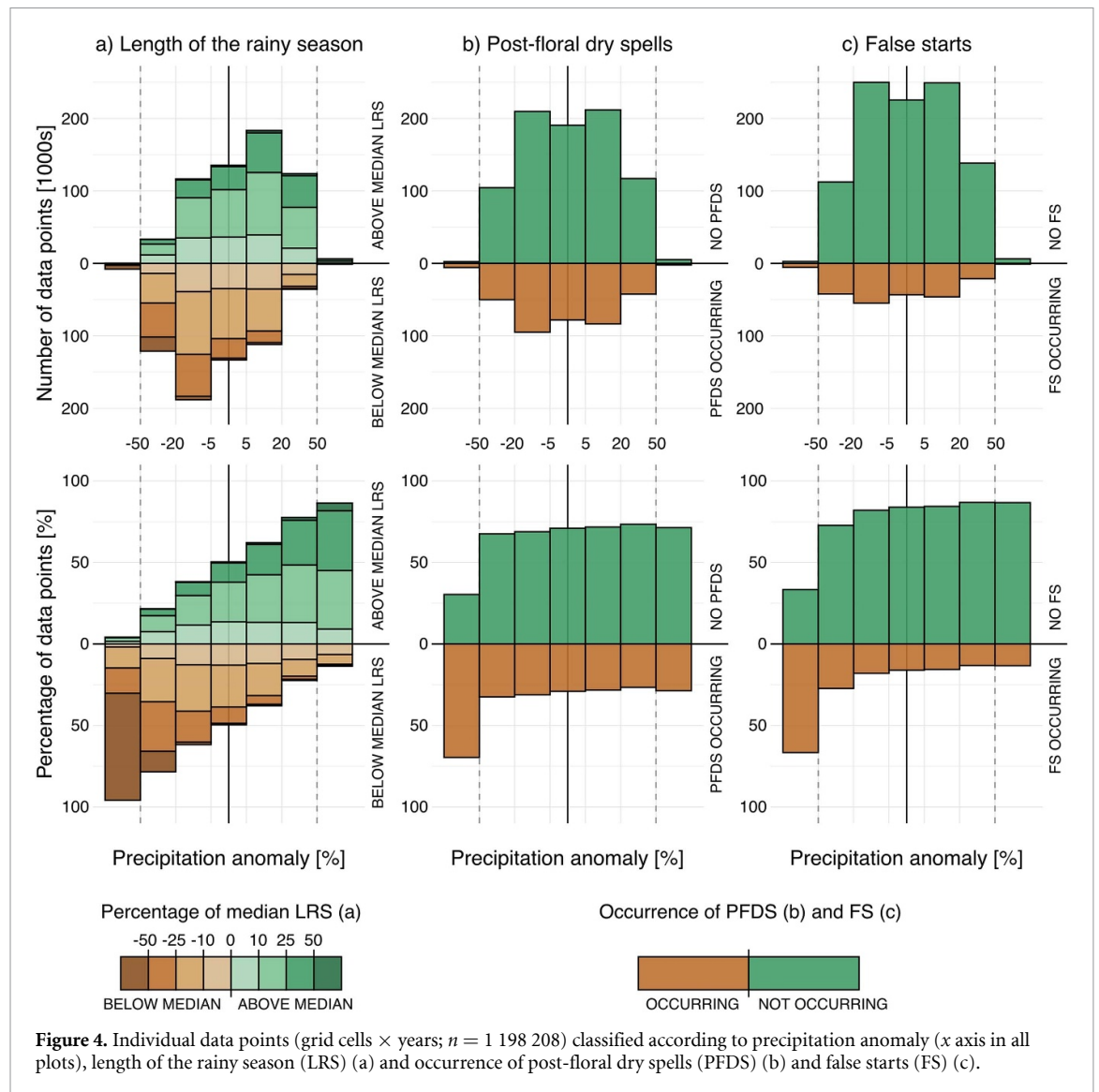|	Among all variables	Among intraseasonal variables		
Spatial coverage	Whole study region	Whole study region	Areas with positive P_a trend (56% of total)	Areas with no or negative P_a trend (44% of total)
Improvements without declines	59.8	40.0	42.9	36.3
No improvements or only declines	25.0	51.7	47.4	57.2
Mixed	15.2	8.3	9.7	6.5

LRS (figure 2(a)), but in a majority of the area, strong correlation could not be found (figure S2).

The association between P_a anomalies and PFDS was much less clear. The likelihood of at least one PFDS during one season changed very little with P_a anomalies ranging from −50% to 50% of average (representing >99% of cases) (figure 4(b)). PFDS were considerably more likely to occur only in exceptionally dry years (i.e. with P_a anomaly <−50% of grid cell average).

Although trends in FS frequency and P_a aligned only in a few relatively small areas (figure 2(c)), the likelihood of FS occurrence did increase somewhat with negative P_a anomalies, such that a FS was almost twice as likely in years with 20%–50% lower than average P_a compared to years with 20%–50% higher than average P_a (figure 4(c)). As with PFDS, likelihood of FS increased substantially in extremely dry years (i.e. where P_a anomaly <−50% of grid cell average).

4. Discussion

Our findings suggest that agriculturally-relevant improvements in rainfall occurred only in some parts of the Sahel: wetting in terms of P_a occurred in about 56% of the study region, while improvements in intraseasonal rainfall characteristics (i.e. at least one variable improving, none declining) were present in 40% of the region (table 2). We did not find a strong association between P_a and the intraseasonal variables: within the areas with increased P_a, improvements in intraseasonal rainfall variables were present in only 43% of the area (as a comparison, improvements occurred in 36% of the areas with no significant trend in P_a; table 2). In other words, improvements in *both* P_a and intraseasonal variables occurred in only 24% of the total area, despite the majority of the region receiving more rain annually. Thus, it seems that in the Sahel, 'wetter' in terms of P_a does not necessarily mean 'better'.

Figure 4. Individual data points (grid cells × years; *n* = 1 198 208) classified according to precipitation anomaly (*x* axis in all plots), length of the rainy season (LRS) (a) and occurrence of post-floral dry spells (PFDS) (b) and false starts (FS) (c).

The association with P_a was particularly weak for PFDS, whose probability of occurrence decreased only slightly even for +20%–50% P_a anomalies compared to negative P_a anomalies of the same magnitude. The contrasting trends between PFDS and FS, which we observed in many regions across Sahel, also suggest that their occurrence could be more related to shifts in seasonality (dry spells shifting from one end of the rainy season to the other) than seasonal rainfall sums.

Our results complement two previous regional analyses of similar rainfall characteristics in the Sahel. Salack *et al* [25] compared the rainy seasons of 1991–2012 with drought years that occurred during 1960–2010. They found that, apart from higher seasonal precipitation sums, recent decades exhibited many drought year characteristics, such as prolonged dry spells. Their results align well with our findings on intraseasonal rainfall variables, as for most of the study area there were no clear improvements since the beginning of the 1980s (most of the '80s falls into the drought year cluster of Salack *et al*), regardless of

whether P_a increased or not (figure 2, table 2). Our analysis extends that of Salack *et al* to also examine spatial variability in rainfall characteristics, and shows that there are some pockets within our study area exhibiting recovery from drought conditions at least to some extent, such as the northern parts of Burkina Faso, western Mali, and areas around the border of Chad and Sudan.

Bichet and Diedhiou [6] used the CHIRPS data to explore trends (1981–2014) in wet and dry spell characteristics in a region in West Africa that includes—but is not limited to—the western parts of our study area (approximately the area west of Niger and Nigeria). Across the overlapping area of our study and that of Bichet and Diedhiou, they found that the average length of dry spells (i.e. two or more consecutive dry days) has decreased. However, our analysis reveals significant spatial variation when dry spells of a specific length and timing (i.e. FS and PFDS) are considered. For most of the overlapping region, shortening average dry spell length did not lead to decreased frequency of years with PFDS, but there are

areas where FS became less frequent—i.e. dry spells after first rains became shorter. Nevertheless, for a clear majority of the overlapping area, shorter average length of dry spells can be explained by short dry spells getting even shorter, which would not necessarily be relevant for agriculture if longer dry spells remain common or become more frequent.

Bichet and Diedhiou [6] conclude that their results do not indicate an increase in drought conditions, contrary to the findings of Salack *et al* [25]. However, a comparison of this paper and the two other analyses suggests that the choice of dry spell metrics, and the spatial extent and resolution of analysis can reveal different aspects of intraseasonal rainfall dynamics in the Sahel and lead to contrasting conclusions.

4.1. Future of Sahelian rainfall

Most models point towards a climate with more rain in the central and eastern parts of Sahel and a drier climate in the western parts around the mid 21st century [38–40]. Increases in rainfall are projected to occur mainly at the end of the rainy season while the decrease in rainfall appears to be associated with a later onset of the rain, i.e. a shift in the seasonality. Rainfall intensity will likely continue to increase, while the number of rainy days decreases [5, 39]. Additionally, evaporative demand is expected to increase with rising temperatures [41, 42], further exacerbating the impacts of rainfall deficits and dry spells. Thus, while parts of the Sahel will potentially receive more rain in the future, intraseasonal rainfall and temperature dynamics are likely to continue to change in ways that are not necessarily beneficial for agriculture.

However, future trends in Sahel rainfall are uncertain, due to (a) intrinsic uncertainties in the drivers of long-term and short-term rainfall variability, (b) poor understanding of those drivers, and (c) misrepresentation of those drivers in climate models [43]. Climate models generally reproduce the seasonal cycle of precipitation over Africa and Sahel well, but have problems with simulating the timing of the rainy season and the spatial heterogeneity [38, 44, 45]. Challenges in model simulation are associated with lesser-known, complex interactions occurring across scales—for example, between local soil moisture and atmospheric stability and the dynamics of regional circulation systems (e.g. the west African Monsoon), mesoscale weather patterns (e.g. convective storms) [5, 46–48], and regional atmospheric moisture balance [49]. Large-scale regional tele-connections have also been suggested to play a role; a substantial part of Sahelian rainfall originates from evaporation from land, particularly in the western and central parts of the Sahel [49–51]. Irrigation in Northern Africa also contributes to Sahelian rainfall due to the east-to-west moisture flows [52], and thus irrigation expansion in that region may further increase the available moisture for Sahelian rainfall [50]. The joint

effects of local and remote land-use change and management on Sahelian rainfall variability are thus still an ongoing scientific inquiry.

4.2. Coping with uncertainty

With so much uncertainty around hydroclimatic change, the survival and success of rainfed agriculture in the Sahel is largely determined by the capacity of farmers to cope with changing rainfall and drought characteristics. Currently, a considerable share of rainfall during the growing season is lost to soil evaporation [53]. Various water and soil management options could improve water productivity through a 'vapour shift' from unproductive evaporation to productive transpiration [54, 55]. For instance, conservation and zero tillage practices can increase water infiltration and soil water holding capacity and mulching can help retain soil moisture, thus increasing water available for crops [56, 57].

While these approaches help mitigate impacts of shorter dry spells, prolonged periods without rain will still require supplemental irrigation to avoid negative yield impacts [3, 23, 58], which could be achieved through various water harvesting methods. However, for water management to be effective, improved soil nutrient management is also required [22, 59]. Other potentially beneficial management interventions include the choice of cultivars between traditional and modern, drought-tolerant varieties [60].

The suggested management options have the potential to not only secure current production levels under variable future conditions, but also increase yields. For instance, Rost *et al* [53] found that shifting 25% of annual soil evaporation to transpiration would increase net primary productivity by >20% in many parts of the Sahel. However, even with such increases, yield levels would remain relatively low, and many economic and social barriers to successful implementation of these management upgrades exist. Moreover, despite these types of investments, the highly variable climate still poses a real risk of frequent crop failures, which could lead to households losing much of their assets in times of droughts, contributing to the existence of poverty traps [61]. Thus, for investments in water system technologies and other management upgrades to make a substantial contribution towards poverty alleviation, they have to be coordinated with other relevant investments, e.g. in infrastructure, markets, and enabling institutions [58, 61].

5. Conclusions

Sahelian hydroclimate has changed relatively rapidly during the past four decades and will continue to change in the future, with implications for agriculture and food security of the growing population. In this paper we have shown that recent increases in annual

rainfall have generally not translated into improved rainfall conditions for agriculture, although exceptions to this were found in some parts of the region. Future hydroclimatic change is expected to bring further intensification and increased variability of rainfall, along with rising temperatures, suggesting that considerable improvements in hydroclimatic conditions for rainfed agriculture are not likely. Improved rainwater and soil management practices could help sustain agricultural livelihoods and secure nutrition in the Sahel, but it will remain a very difficult task.

Data availability statement

The data that support the findings of this study are available upon request from the authors.

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