

Future changes in wet and dry season characteristics in CMIP5 and CMIP6 simulations

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1 **Future Changes in Wet and Dry Season Characteristics in CMIP5 and**
2 **CMIP6 simulations**

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ABSTRACT

13 Climate change will result in more dry days and longer dry spells, however, the resulting impacts on
14 crop growth depend on the timing of these longer dry spells in the annual cycle. Using an ensemble
15 of Coupled Model Intercomparison Project Phase 5 and Phase 6 (CMIP5 and CMIP6) simulations,
16 and a range of emission scenarios, here we examine changes in wet and dry spell characteristics
17 under future climate change across the extended tropics in wet and dry seasons separately. Delays
18 in the wet seasons by up to two weeks are projected by 2070-2099 across South America, Southern
19 Africa, West Africa and the Sahel. An increase in both mean and maximum dry spell length during
20 the dry season is found across Central and South America, Southern Africa and Australia, with
21 a reduction in dry season rainfall also found in these regions. Mean dry season dry spell lengths
22 increase by 5-10 days over north-east South America and south-west Africa. However, changes
23 in dry spell length during the wet season are much smaller across the tropics with limited model
24 consensus. Mean dry season maximum temperature increases are found to be up to 3°C higher
25 than mean wet season maximum temperature increases over South America, Southern Africa and
26 parts of Asia. Longer dry spells, fewer wet days, and higher temperatures during the dry season
27 may lead to increasing dry season aridity, and have detrimental consequences for perennial crops.

28 **1. Introduction**

29 Climate change will result in more dry days and longer dry spells; this has the potential to lead
30 to negative impacts on crop yields and food security, as water stress limits crop growth. Across the
31 tropics most crops are grown solely during the annual wet season, with few crops grown during
32 the dry season. Therefore the timing of these longer dry spells in the annual cycle is of crucial
33 importance in determining their impact.

34 As the climate warms, the contrasting constraints of energy budgets at global scales and moisture
35 budgets at regional scales drive a general increase in precipitation intensity and decrease in fre-
36 quency that are further altered as atmospheric circulation patterns shift in location (Trenberth 2011;
37 Held and Soden 2006; Funk et al. 2019; Giorgi et al. 2019; Allan et al. 2020). A larger increase in
38 precipitation intensity compared to mean precipitation is balanced by a decrease in the number of
39 wet days, resulting in longer dry spells and shorter wet spells (Giorgi et al. 2011; Seneviratne et al.
40 2012; Sillmann et al. 2013b). These longer dry spells may have negative impacts on crop yields
41 and food production (Rockström et al. 2010), as reductions in water availability limit crop growth.
42 Heavier rainfall events punctuating longer dry spells can also affect hydrological characteristics;
43 for example, more rainfall can be taken up by the soil rather than producing runoff yet on the other
44 hand, more intense rainfall falling on encrusted ground can lead to higher runoff (Eekhout et al.
45 2018; Yin et al. 2018).

46 Many studies have reported an increase in the number of dry days and dry spell lengths under
47 future climate change. Giorgi et al. (2019) found an increase in the number of dry days and dry
48 spell lengths and a decrease in wet spell lengths aggregated over land areas in the tropics and the
49 extra-tropics over the 21st century in 10 Coupled Model Intercomparison Project Phase 5 (CMIP5)
50 model projections. Giorgi et al. (2014) report that the response in wet and dry spell lengths is more

51 pronounced and spatially consistent over the tropics than the extratropics. Polade et al. (2014)
52 also identified an increasing dry day frequency, in particular over northern South America, Central
53 America, Southern Africa and the Mediterranean; regions also identified by Pascale et al. (2016)
54 as showing increases in the number of dry days. While Giorgi et al. (2014) and Giorgi et al. (2019)
55 examined the mean wet and dry spell lengths over large land areas, Sillmann et al. (2013b) looked
56 at the maximum wet and dry spell lengths over a number of regions. They find significant increases
57 in maximum dry spell length over Central America, parts of South America, the Mediterranean,
58 Southern Africa, and south and south-east Asia, (consistent with the regions where Polade et al.
59 (2014) found more dry days) with decreases in maximum dry spell length over the high northern
60 latitudes, north-east Asia and East Africa. Lau et al. (2013) also suggest increasing dry spell
61 lengths over Southern Africa, the Mediterranean and parts of South America, although they use a
62 threshold of $<0.024 \text{ mm day}^{-1}$ to look at the changes in the frequency of dry months. Overall, the
63 Intergovernmental Panel on Climate Change (IPCC) Special Report on Extremes concluded that
64 an increase in dry spell length and frequency was very likely over the Mediterranean and southern
65 Australia, and likely over most subtropical regions (Seneviratne et al. 2012).

66 Most of these previous studies have looked at changes in wet and dry spells across the entire
67 calendar year (Sillmann et al. 2013b). In the tropics, however, most crops are grown during the
68 annual wet season. Therefore the impact of longer or shorter wet and dry spells may vary throughout
69 the year. Longer dry spells during the main wet season may have significant detrimental impacts
70 on agriculture, whereas longer dry spells within the period of the year that is climatologically
71 dry may have less impact. Conversely, longer wet spells within the dry season may be beneficial
72 e.g. for recharging water supplies. Therefore, understanding the timing of changes in wet and
73 dry spell lengths is of crucial importance. Orłowsky and Seneviratne (2012) looked at changes
74 in consecutive dry days (CDD) in the four meteorological seasons and found some differences in

75 the projected changes in different seasons; for example, over Asia there is a decrease in CDD in
76 December-February (DJF), but an increase in June-August (JJA). The magnitude of changes was
77 also different in different seasons; for example, over Southern Africa the increase in CDD was
78 greater in JJA than in DJF. However, these 3-month meteorological seasons may not map directly
79 onto wet and dry seasons and there may be changes in wet and dry season length in the future
80 (Dunning et al. 2018). Other studies looking at changes in wet and dry spell lengths in wet seasons
81 have focused over certain regions, for example, Klutse et al. (2018) looked at changing wet and dry
82 spell lengths in June-September over West Africa, and Mba et al. (2018) examined changing wet
83 and dry spell lengths in March-May and September-November over Central Africa. Furthermore,
84 very few studies have also considered the impact of temperature changes; increases in temperature
85 combined with longer dry spells may lead to reductions in soil moisture and increased water stress
86 for crops. Changes in extreme temperatures may differ in wet and dry seasons, hence it is important
87 to separately examine the wet and dry seasons, so as not to exaggerate the impact of temperature
88 changes on agriculture.

89 Although the seasonal timing of changes in wet and dry spells is of significant societal importance,
90 it has not been investigated consistently in previous studies. Many studies have found a trend of
91 wet seasons getting wetter and dry seasons getting drier under future climate change (Chou et al.
92 2013; Kumar et al. 2015; Schurer et al. 2020), suggesting there may be notable seasonal differences
93 in wet and dry spell projections. Thus, the aim of the present study is to answer the question
94 "Do changes in the length of wet and dry spells differ in climatologically wet and dry seasons?".
95 Unlike previous dry spell studies, a recently developed methodology is used to determine the
96 timing of the wet and dry season at each location (Liebmann et al. 2012; Dunning et al. 2016),
97 thus enabling investigation of changes in the wet and dry season using a location-specific, not
98 month-based, seasonal definition. Furthermore, we utilise projections from the latest version of

99 coupled global climate models, which have recently been released (Coupled Model Intercomparison
100 Project Phase 6, CMIP6, Eyring et al. 2016); these are of higher resolution with more complex
101 models than the previous generation of coupled global climate models (CMIP5, Taylor et al. 2012),
102 and thus represent a new opportunity for exploring changes in daily quantities. Here, results
103 from both CMIP5 and CMIP6 are compared, using a range of emissions scenarios. Many previous
104 studies have used the well-established Climdex (<https://www.climdex.org/>) indices to explore
105 changes in wet and dry spells (Zhang et al. 2011; Seneviratne et al. 2012; Sillmann et al. 2013b).
106 These define CDD (Consecutive Dry Days; maximum length of dry spell) and CWD (Consecutive
107 Wet Days; maximum length of wet spell) as "the maximum number of consecutive days with daily
108 precipitation less than/greater than 1mm day^{-1} " (for CDD/CWD respectively). This therefore only
109 looks at the longest wet/dry spell in a year. In this study we aim to look at a more complete set of
110 metrics, including number of wet days and mean length of wet/dry spells, to gain a more complete
111 picture of how wet and dry spells are changing under future climate change. Along with changes
112 in wet and dry spells, changes in maximum temperatures are also considered, as large temperature
113 increases may exacerbate the impacts of long dry spells.

114 **2. Data and Methodology**

115 *a. Model Data*

116 Daily precipitation data were used from 31 CMIP5 (Coupled Model Intercomparison Project
117 Phase 5, Taylor et al. 2012) models and 19 CMIP6 (Coupled Model Intercomparison Project Phase
118 6, Eyring et al. 2016) models under a medium (Representative Concentration Pathway (RCP) 4.5/
119 Shared Socioeconomic Pathway (SSP) 245) and high (RCP8.5/SSP585) emissions scenario; a full
120 list of models used is included in Tables S1 and S2. SSP585 is the highest emissions scenario and

121 represents an update to the RCP8.5 emissions scenario (the highest emission scenario for CMIP5);
122 both produce a radiative forcing of 8.5 W m^{-2} in 2100 (Van Vuuren et al. 2011; O’Neill et al. 2016).
123 While some have argued that this pathway is unrealistic, it should be noted that current emissions
124 are in line with the RCP8.5 scenario (Schwalm et al. 2020). The SSP245 scenario represents a
125 medium emissions scenario and updates the RCP4.5 pathway; both produce a radiative forcing of
126 4.5 W m^{-2} in 2100 (Van Vuuren et al. 2011; O’Neill et al. 2016).

127 Models were selected based on the availability of daily precipitation data for historical and
128 RCP4.5/RCP8.5 (CMIP5) or SSP245/SSP585 (CMIP6) simulations for periods at the end of the
129 20th and 21st centuries. For the present day climate, the historical simulation was used over the
130 period 1 January 1985 - 31 December 2014, chosen to be in line with IPCC AR6. For the CMIP5
131 simulations the historical simulation is only available until 31 December 2005; CMIP5 RCP4.5
132 simulations were used for 1 January 2006 - 31 December 2014 (taken from the same model) and
133 appended to the historical simulations for 1 January 1985 - 31 December 2005. Recent analysis
134 suggests that CO_2 emissions have been above RCP4.5 levels over the recent period, so this gives a
135 conservative estimate (Schwalm et al. 2020). Projections from RCP4.5 and RCP8.5 do not differ
136 significantly over this 2005-2014 period, therefore the choice of scenario was assumed to have a
137 minimal impact. Furthermore, the primary focus is on the newer CMIP6 models; results from the
138 CMIP5 models are mainly presented for traceability with previous studies. The period 1 January
139 2070 - 31 December 2099 was used for the end of the 21st century period. Only the first ensemble
140 members were used (r1i1p1/r1i1p1f1) – for two CMIP6 models r1i1p1f2 was used due to r1i1p1f1
141 being unavailable (see Table S2). Other studies have taken a similar approach. Daily maximum
142 temperature data were also used for the same set of models and time periods, however, they were
143 unavailable for a couple of the models at the time when the analysis was conducted; this is indicated
144 in Table S2.

145 Data were considered over the region 50°S-50°N. The focus here is on differences in wet and
146 dry seasons so the decision was taken to focus on this tropics and sub-tropics region that has a
147 well defined wet season (equatorward parts of mid-latitudes are also included in 50°S-50°N); high
148 latitude regions tend to have less well-defined wet and dry seasons and thus are not included. All
149 analysis was done on the models at native resolution. For the multi-model median maps the metrics
150 were first computed at the native resolution and were then regridded onto the lowest resolution grid
151 using nearest-neighbouring remapping. For the regional analysis the regions were calculated for
152 each model grid and the model's native resolution grid was used.

153 *b. Observational Data*

154 CHIRPS (Climate Hazards group Infrared Precipitation with Stations) precipitation data were
155 used over 50°S-50°N for 1 January 1985 – 31 December 2014 (to be comparable to historical
156 CMIP6 simulations). CHIRPS precipitation estimates use thermal infrared imagery and gauge
157 data in addition to a monthly precipitation climatology, CHPClim (Climate Hazards Center's
158 Precipitation Climatology) and CFS (Coupled Forecast System) version 2 reanalysis fields to
159 produce rainfall estimates (Funk et al. 2015).

160 *c. Methodology*

161 To calculate metrics, including mean wet and dry spell lengths, for wet and dry seasons separately,
162 each grid point is first classified into one of four seasonality categories (section 1), then season
163 start and end dates are computed using a methodology for objectively calculating wet season onset
164 and cessation dates (section 2). Metrics are then calculated for wet and dry seasons separately
165 (section 3).

166 1) SEASONALITY CLASSIFICATION

167 The seasonality of precipitation varies across the tropics from monsoonal regions with one
168 summer wet season per year, to dry desert regions with little rainfall, to rainforest regions that are
169 wet year round. East Africa is known to experience two wet seasons per year (Yang et al. 2015).
170 To distinguish between wet and dry seasons, it is first important to determine the seasonal regime.

171 A number of different methodologies have been utilised for this purpose; Herrmann and Mohr
172 (2011) used monthly precipitation and temperature to define rainfall seasonality regimes across
173 Africa. Pascale et al. (2016) and Feng et al. (2013) used the Relative Entropy and Dimensionless
174 Seasonality Index to define and examine changes in the ‘Global Monsoon Domain’. Liebmann
175 et al. (2012) and Dunning et al. (2016) use harmonic analysis to separate regions with one or two
176 wet seasons per year across Africa. A combination of these metrics is used here.

177 It was decided that four categories need to be distinguished: regions that are dry year-round,
178 regions that are wet year-round, regions with one wet season per year (annual regime), and regions
179 with two wet seasons per year (biannual regime). While Herrmann and Mohr (2011) defined
180 additional regimes, here just four are used for simplicity. The methodology used has three steps:

- 181 1. The mean annual rainfall was computed at each land grid point (between 50°S and 50°N).
182 The 20% of driest land grid points were excluded as dry regions with no marked wet season.
- 183 2. Grid points with a relative entropy (a measure of how uniform or variable the seasonal
184 sequence of monthly rainfall is, see below) less than 0.3 were defined as wet year round with
185 no marked wet/dry seasons.
- 186 3. The remaining grid points were defined as having one/two wet seasons per year based on the
187 ratio of the amplitude of the second harmonic to the amplitude of the first harmonic. If the

188 ratio is greater than 1/less than 1 then the grid point experiences a biannual/annual regime
189 with two/one wet season(s) per year.

190 The relative entropy quantifies how different the observed sequence of monthly rainfall is from
191 a uniform monthly sequence with unchanging monthly rainfall. The relative entropy attains the
192 maximum value when the annual rainfall is concentrated in one single month, and equal to 0 for a
193 uniform precipitation sequence (Feng et al. 2013; Pascale et al. 2016). Details of the calculation
194 of relative entropy are in the Supplementary Information.

195 Regions that are wet year round have a low value of relative entropy. Pascale et al. (2016) defined
196 the 'Global Monsoon Domain' to be where $D_k > 0.4$ (and where the Dimensionless Seasonality
197 Index is >0.05 , but this is mainly used to remove dry regions), but when examining changes in
198 the timing of the rainfall centroid Pascale et al. (2016) used a relative entropy threshold of 0.3 to
199 "exclude regions without a pronounced dry season". Here a threshold of 0.3 is used; a range of
200 thresholds were considered and it was decided that a D_k threshold of 0.3 classified regions such as
201 the Maritime Continent, Central Africa and eastern North America, known to be wet year round,
202 correctly, while also classifying most of South America as having an annual regime. The aim was
203 to just exclude those points that are definitely wet year round (without a pronounced dry season),
204 as opposed to just including those with a well-defined monsoon, hence the threshold of 0.3 was
205 used.

206 The seasonality classification for CHIRPS (Figure 1) shows that the dry desert regions (including
207 the Sahara and Gobi Deserts, and the Arabian Peninsula) are correctly identified as dry-year-round,
208 Central Equatorial Africa and the Maritime Continent are correctly identified as wet year-round,
209 and the Horn of Africa is categorised as biannual. Monsoon regions, such as India, East Asia
210 and South America are correctly identified as experiencing an annual regime. Over Africa, the

211 classification is similar to that produced by Herrmann and Mohr (2011). This classification gives
212 an overall picture – in regions of complex rainfall regimes, with multiple rainfall peaks separated
213 by a relatively drier period lasting only one to two months (e.g. Central America; Small et al.
214 2007) it may not capture this complex seasonal regime, and defines the region as having one wet
215 season per year.

216 The seasonality classification was calculated for each model and scenario; it was calculated
217 separately for the present and future periods. Figure 1 shows the seasonality mask for CHIRPS,
218 and the modal seasonality classification for CMIP6 historical (for CMIP5 and all scenarios see
219 Figure S1). For the most part the model seasonality classification shows good agreement with
220 CHIRPS with a few minor differences; southern Australia and eastern China are shown as having
221 one wet season in models whereas they are defined as wet year round in observations. In terms
222 of the future projections there are not large changes in the overall pattern of seasonality (<10% of
223 grid points change regime), and most changes are located on regime boundaries (Figure S1). The
224 notable changes are over southern Europe/middle East where we see changes from wet year round
225 to an annual regime, and over central Africa CMIP6 shows some grid points change from wet year
226 round to two wet seasons per year; presumably due to larger rainfall increases in the wetter seasons
227 than the drier seasons.

228 2) WET AND DRY SEASON DISTINCTION

229 The method of anomalous accumulation was used to determine start and end dates of the
230 climatological wet and dry seasons. This method is suitable for application at a global scale as
231 it does not use a set precipitation threshold, and therefore can be applied to regions with very
232 different rainfall amounts (Liebmann et al. 2012; Dunning et al. 2016). It is applicable to regions

233 with both one and two wet seasons per year (Dunning et al. 2016). Full details of the calculation
234 can be found in the Supplementary Information.

235 Onset and cessation dates were calculated for each model and scenario; thus accounting for
236 changing seasonal timing under future climate change. Historical patterns of onset and cessation
237 in the CMIP5 and CMIP6 models were similar to those produced using observations, with a wet
238 season during the boreal summer in the northern hemisphere and a wet season during the austral
239 summer in the southern hemisphere (see Figure S2-6 in the Supplementary Information); Dunning
240 et al. (2017) showed that CMIP5 models generally captured the correct patterns of onset and
241 cessation across Africa, when assessed using this methodology.

242 3) WET AND DRY SPELL METRICS

243 A range of metrics were calculated for wet and dry seasons. The wet season was defined to be
244 the period after the onset and before the cessation date, while the dry season was defined to be the
245 period between the cessation date and the onset date. For the metrics calculated here, a threshold
246 of 1 mm day^{-1} was used to define a wet/dry day. The well-established Climdex indices also use
247 a threshold of 1 mm day^{-1} to define wet/dry days for the calculation of CWD and CDD, used in
248 Seneviratne et al. (2012) and Sillmann et al. (2013b). Other studies looking at wet and dry days
249 and spells also use a threshold of 1 mm day^{-1} (Polade et al. 2014; Giorgi et al. 2014; Funk et al.
250 2019; Giorgi et al. 2019), and this is confirmed by analysis of cumulative frequency of daily rainfall
251 (Figure S7).

252 The following metrics were calculated:

- 253 • Wet/Dry Season Rainfall: Sum of daily rainfall over the wet/dry season.
- 254 • Wet/Dry Season Rainy Days: The number of days with rainfall greater than 1 mm day^{-1} in
255 the wet/dry season.

- 256 • Wet/Dry Season Rain per Rainy Day: The mean rainfall over all days with rainfall greater
257 than 1 mm day⁻¹ in the wet/dry season.
- 258 • Maximum wet/dry spell length in wet/dry seasons: The length (in days) of the longest wet/dry
259 spell in each wet/dry season.
- 260 • Mean wet/dry spell length in wet/dry seasons: The mean length (in days) of all wet/dry spells
261 (of length two days or more) in the wet/dry season.
- 262 • Wet/Dry Season Mean Maximum Temperature: The mean of the daily maximum temperature
263 over the wet/dry season.

264 Metrics were computed for one wet season for the annual regime region and for two wet seasons
265 for the biannual regime regions. For the wet-year-round regions the metrics were calculated for
266 each calendar year (wet season was assumed to last all year); these points have a wet season but
267 no dry season, so are included in wet season plots but not dry season plots. The median was taken
268 over all seasons and the historical and future periods compared. For the maps, the change was
269 regridded onto the lowest resolution model using nearest-neighbour remapping.

270 Figure 2 and Figure S8 show that the historical simulations from the CMIP5 and CMIP6 models
271 capture the observed distribution of wet and dry spells in wet and dry seasons as found in CHIRPS.
272 The main difference is the mean length of wet spells in the wet season where the CMIP6 models
273 contain much longer wet spells than the observations. Similarly, Sillmann et al. (2013a) found good
274 model representation of CDD in the CMIP5 models, but found that CWD was overestimated in
275 both models and reanalyses. Results from a second observational dataset (Multi-Source Weighted-
276 Ensemble Precipitation (MSWEP, Beck et al. 2019); Figure S9) are very similar to those shown in
277 Figure 2 for CHIRPS. The mean length of wet spells in the wet season is longer in MSWEP over
278 parts of South America, Ethiopia and the Himalayas in MSWEP, presumably due to the inclusion

279 of reanalysis data, but the mean lengths in CMIP6 still exhibit a positive bias over these regions
280 when compared with MSWEP.

281 4) REGIONS

282 To explore changes over certain regions a regional classification was required. The regions used
283 here are those defined for the 6th IPCC report (Iturbide et al. 2020). The locations and regions
284 used are shown in Figures 6a, 8a and 10a.

285 5) TIMESERIES ANALYSIS

286 Timeseries were produced for certain regions to examine the changes over the whole period
287 (1985-2099). The regions for timeseries were selected over areas of particular interest, where
288 significant changes in wet/dry spell length had been identified. For the timeseries it is assumed
289 that all grid points have an annual regime; for the three regions used (NES, SEAF and WAF) this
290 is a reasonable assumption (Figure 1).

291 When calculating the timeseries of wet/dry spell lengths over the IPCC regions two methodologies
292 were employed. The first methodology defined a climatological onset and cessation date using the
293 full 115 years of the timeseries and then used the same onset and cessation date for each year, thus
294 not accounting for changes in seasonal timing. The wet and dry spell lengths were then calculated
295 for each year, in the same manner as above. The second methodology used a moving 30-year
296 period to calculate the onset and cessation dates, with the first 15 and last 15 years of the full
297 record set to the first-30-years value and the last-30-years value. Thus this second methodology
298 takes into account changes in seasonal timing. In section 3, timeseries produced using the second
299 methodology were presented. For the most part the differences between the two methodologies
300 were similar.

3. Results and Discussion

Results are presented here for wet and dry seasons; section 3a on seasonal timing presents changes in timing of the onset and cessation of the wet season, while sections 3b-3e present changes in rainfall and temperature metrics for wet and dry seasons separately. Figure S2 in the Supplementary Information indicates the timing of the wet season(s) in the calendar year for reference.

a. Seasonal Timing

The multi-model median change in onset and cessation of the annual wet season in CMIP6 under the SSP585 scenario, shown in Figure 3, shows that onset is projected to get later across South America, Southern Africa, West Africa and the Sahel, with changes of up to two weeks. Over South America this continues the recent trend of delayed onset found by Correa et al. (2020). Over East Asia Figure 3 shows the onset is projected to be earlier, with advances of over a week in some locations. Changes in cessation are smaller than changes in onset; Figure 3b shows later cessation by up to a week over the Sahel, and parts of Asia, with the largest changes of around two weeks over central America. These results show good agreement with previous studies of changing onset over Africa (Dunning et al. 2018), and over Asia, with Kitoh et al. (2013) reporting a later retreat over South Asia and Ha et al. (2020) reporting an earlier onset over East Asia. The results also show good agreement with Pascale et al. (2016), who analysed changes in the timing of the rainfall centroid, and found a delay over Africa, Central and South America and parts of South Asia, with an advance over East Asia. More broadly, a number of studies have found a global phase delay of the seasonal cycle of precipitation (Biasutti and Sobel 2009; Dwyer et al. 2014; Marvel et al. 2017) and a redistribution of rainfall from early to late in the monsoon season (Seth et al. 2013), in agreement with the generally later onset/cessation shown in Figure 3. A number of mechanisms have been proposed for this; Dwyer et al. (2014) linked the delay to changes in the seasonality of

324 the circulation, Seth et al. (2013) linked the delay to an enhanced spring convective barrier, while
325 Song et al. (2018) linked the delay to changes in cross-equatorial energy transports and change in
326 the strength of the subtropical highs.

327 *b. Seasonal Rainfall Characteristics*

328 Firstly, changes in seasonal rainfall totals, seasonal number of rainy days and seasonal rain per
329 rainy day were explored; Figure 4 shows the changes from CMIP6 under SSP585. South and East
330 Asia, Eastern Africa and Eastern North America all show projected increases in wet season rainfall
331 (Figure 4a); due to a combination of increasing rainfall intensity in the wet season (Figure 4e) and
332 either limited change or a slight increase in the number of wet days in the wet season (Figure 4c).
333 Wang et al. (2021), Wang et al. (2020) and Collins et al. (2013) also show an increase in boreal
334 summer rainfall over South and East Asia; Wang et al. (2020) show increases of around 1 mm
335 day⁻¹ in JJAS over South and East Asia. The Mediterranean, Central America and northern South
336 America exhibit significant decreases in wet season rainfall (of 5-25%, Figure 4a); these regions
337 also experience a significant decrease in the number of rainy days in the wet season (decrease of
338 over 15 days, Figure 4c), and smaller increases in rain per rainy day (Figure 4e). The asymmetry
339 between the American and Asian-African monsoon systems, with the North American monsoon
340 getting drier and the Asian-African monsoon getting wetter, identified in other studies (e.g. He
341 et al. 2020), is apparent in Figure 4. Other regions, including Southern Africa, the Maritime
342 Continent, and parts of southern Europe, also exhibit a decrease in the number of wet season
343 rainy days (Figure 4c). However, a significant decrease in rainfall is not found in these regions
344 (Figure 4a) as the decrease in the number of rainy days is compensated by an increase in rain per
345 rainy day (Figure 4e), broadly consistent with expectations from joint thermodynamic and energetic
346 constraints (Allen and Ingram 2002; Trenberth 2011).

347 Considering the dry season, Central America, South America, Southern Africa and Australia
348 all show decreases in dry season rainfall (Figure 4b), decreases in the number of wet days in the
349 dry season (Figure 4d) and little change in dry season rain per rainy day (Figure 4f). A decrease
350 in boreal summer rainfall over Southern Africa is also found by Wang et al. (2021), Wang et al.
351 (2020), and Collins et al. (2013), and a number of studies have identified an increasing contrast
352 between wet and dry seasons, with wet seasons getting wetter and dry seasons getting drier (Chou
353 et al. 2013; Kumar et al. 2015; Polson and Hegerl 2017; Lan et al. 2019; Deng et al. 2020; Schurer
354 et al. 2020). Eastern Africa, the Eastern Sahel and East Asia all show increases in dry season
355 rainfall (Figure 4b), increases in the number of dry season rainy days (Figure 4d) and increases in
356 dry season rain per rainy day (Figure 4f). Rainfall increases over East Asia are in good agreement
357 with Wang et al. (2021), Wang et al. (2020), and Collins et al. (2013) who identified increased
358 boreal winter rainfall in this region. In general, the increases in dry season rain per rainy day are
359 less than the increases in wet season rain per rainy day. Changes in seasonal rainfall are shown as
360 a percentage of the wet/dry season rainfall; thus while changes in dry season rainfall may appear
361 larger, in absolute terms the changes in wet season rainfall are larger. Central and northern South
362 America show rainfall decreases in both seasons, in agreement with Wang et al. (2020) who also
363 show precipitation decreases over the region in boreal summer and winter, although in winter they
364 find increases over the east and west coast, although it should be noted that they use a month-based
365 seasonal definition, and the increases are very close to the coast, which may have been removed in
366 the land-sea mask applied here.

367 Changes from CMIP6 under SSP245 and from CMIP5 under RCP8.5 (Figure S10-11) were
368 generally of the same sign of those shown in Figure 4, but of lower magnitude, possibly related to
369 the higher climate sensitivity in CMIP6 than in CMIP5 (Meehl et al. 2020). Over northern South
370 America decreases in dry season rainfall were ubiquitous, but decreases in wet season rainfall were

371 only found in CMIP6 under SSP585. Although they all show a decrease in the number of wet
372 season rainy days over northern South America, CMIP5 RCP8.5 shows a larger increase in wet
373 season rain per rainy day, and CMIP6 SSP245 has a smaller decrease in the number of rainy days,
374 but similar change in rain per rainy day to CMIP6 SSP585. Increases in wet season rainfall over
375 Eastern Africa and South and East Asia, and increases in dry season rainfall over East Africa and
376 East Asia, were found to be robust across the three scenarios and CMIP eras. Decreases in dry
377 season rainfall over Southern Africa were present in all three scenarios and CMIP eras, but were
378 only significant under SSP585 and RCP8.5.

379 *c. Wet and Dry Spells*

380 Figure 5 shows the projected changes in the mean length of wet and dry spells in wet and dry
381 seasons from CMIP6 under SSP585; the changes in maximum spell length are generally of the
382 same sign and of larger magnitude (see Figure S14).

383 During the dry seasons, projections indicate longer dry spells over Central America, north-east
384 South America, Southern Africa and Australia, with increases of up to 10 days (Figure 5a). This
385 is consistent with Figure 4 which showed reductions in dry season rainfall and fewer dry season
386 rainy days over these regions. Shorter dry spells in the dry season are found over East Africa and
387 parts of the Sahel, and East Asia (Figure 5a); these regions showed increases in dry season rainfall
388 and more rainy days in the dry season (Figure 4). Orłowsky and Seneviratne (2012) also show
389 increases in CDD over Southern Africa in JJA (local dry season). Over northern South America,
390 Orłowsky and Seneviratne (2012) show increases in CDD in different regions in all four seasons,
391 with the smallest increases in DJF (the peak of the wet season), thus agreeing on the projection
392 of longer dry spells in the dry season, but also demonstrating the impact of different definitions

393 of seasonality. Sillmann et al. (2013b) also show large increases in CDD over north-east South
394 America, Southern Africa, Australia and central America.

395 For the mean length of dry spells in the wet season (Figure 5b) the changes are generally
396 very small (multi-model median is generally less than half a day) and not statistically significant.
397 Only Southern Europe and the northern Mediterranean shows a statistically significant increase in
398 dry spell length in the wet season; the signal is also seen over the same region for dry seasons
399 (Figure 5a). Parts of the Mediterranean are classified as having one wet season per year, while
400 other parts are wet year round, thus Figure 5a-b indicates a general increase in dry spell length
401 in this region. Other studies, including Orłowsky and Seneviratne (2012) and Seneviratne et al.
402 (2012) show increases in CDD in the Mediterranean; and Brogli et al. (2019) show year-round
403 decreases in Mediterranean rainfall.

404 The changes in the mean length of wet spells are generally of smaller magnitude than the changes
405 in the mean length of dry spells (Figure 5c-d). The only statistically significant change in the mean
406 length of wet spells in the dry season is over northern South America, which shows a decrease
407 in the mean length of wet spells in the dry season; but the magnitude of the change is small
408 (Figure 5c). Only two regions show significant changes in the mean length of wet spells in the
409 wet season (Figure 5d); Central and northern South America and West/Central Africa both show
410 decreases of less than five days. These are the regions with the longest wet spells during the wet
411 season in current climate (Figure 2), and therefore are likely to exhibit the largest changes. These
412 regions also show fewer wet season rainy days under future climate change (Figure 4c), consistent
413 with shorter wet spells.

414 Again, changes from CMIP6 under SSP245 and from CMIP5 under RCP8.5 (Figure S12-13,S15-
415 16) were generally of the same sign of those shown in Figure 5, but of lower magnitude. For the
416 mean length of dry spells in the dry season, increases were present across Central America, north-

417 east South America, Southern Africa and Australia in all three scenarios and CMIP eras, but the
418 magnitude and statistical significance was reduced, particularly under SSP245 where only Southern
419 Africa and small parts of South America showed a statistically significant increase. For the mean
420 length of wet spells in the wet season, the signal was similar in CMIP5 RCP8.5 to CMIP6 SSP585,
421 but much reduced in CMIP6 SSP245, with only the decrease over northern South America present.

422 Figure 3 showed changes in the length of wet and dry seasons under future climate change, which
423 may affect the length of wet and dry spells. Therefore the analysis was repeated, calculating wet and
424 dry spell lengths as a percentage of the wet/dry season length; results were similar demonstrating
425 that the changes found here are not a consequence of changing season lengths.

426 Overall, Figure 5a-b indicates that the significant increases in dry spell length expected under
427 future climate change are projected to occur during the dry season not the wet season. Only parts
428 of the Mediterranean and southern Europe, where some locations experience rainfall year round,
429 show a significant increase in dry spell length in the wet season. Therefore agriculture grown solely
430 during the wet season may be less affected by longer dry spells. However, Figures 4-5 indicate
431 longer dry spells, fewer rainy days, and less rainfall during the dry season in certain regions, which
432 may make the dry seasons more intense, negatively impacting perennial crops and crops grown
433 during the dry season.

434 *d. Regional Changes*

435 Figures 4-5 have presented changes across the tropics; three regions are now considered in more
436 detail. Some of the largest changes in wet and dry spell lengths identified in Figures 4-5 were for
437 northern South America and Africa; hence these regions are explored further. South and East Asia
438 is a region of high population density, highly dependent on agriculture, so this region has also been
439 considered in more detail.

440 1) NORTHERN SOUTH AMERICA

441 Decreases in precipitation over northern South America under future climate change have been
442 widely reported (Scheff and Frierson 2012; Wang et al. 2020), and linked to changes in the tropical
443 Pacific (Parsons 2020) and the response of vegetation to elevated CO₂ (Richardson et al. 2018).
444 Recent declines in dry season precipitation over tropical South America can be attributed to
445 elevated greenhouse gases and land use change (Barkhordarian et al. 2018), while recent increased
446 frequency of dry days over the southern Amazon has been linked to tropical North Atlantic warming
447 and enhanced subsidence of the southern branch of the Hadley cell (Espinoza et al. 2019). Three
448 of the IPCC AR6 regions are considered; South American Monsoon (SAM), north South America
449 (NSA) and north-east South America (NES). Figure 6b-c shows there is generally good model
450 agreement in the projection of longer dry spells in the dry season across all three regions; for all
451 scenarios the 25th percentile (across the models) is above 0. Under the high emissions scenarios
452 for CMIP5 and CMIP6 the median increase in the maximum length of dry spells in the dry season
453 ranges between 9 and 26 days, with median increases in the mean length of dry spells in the dry
454 season between 1.4 and 9.4 days. In their analysis of changes in CWD and CDD over Brazil in the
455 CMIP5 models, Avila-Diaz et al. (2020) also found longer dry spells under future climate change,
456 with the largest increases in the north-east. This is a continuation of the recent trend of longer dry
457 spells in north-east Brazil over 1980-2016 (Avila-Diaz et al. 2020).

458 For the mean and maximum length of wet spells in the wet season the 25th percentile is below
459 0 for all regions and scenarios indicating strong model agreement on shorter wet spells in the wet
460 season under future climate change (Figure 6d-e). Under the high emissions scenarios for CMIP5
461 and CMIP6 median decreases in the maximum length of wet spells in the wet season range between
462 3 and 13 days, while median decreases in the mean length of wet spells in the wet season range

463 between 0.6 and 3.7 days. It is interesting to note that the largest changes in dry spell lengths
464 are over NES, while the largest changes in wet spell lengths are over NSA; this is consistent with
465 Avila-Diaz et al. (2020) who found the largest decreases in CWD over the central northern part of
466 Brazil.

467 For both variables and all the regions the changes are larger for the CMIP6 high emissions
468 scenario than the CMIP5 high emissions scenario; this was also noted in the previous section and
469 is thought to be related to the higher climate sensitivity in CMIP6 than in CMIP5 (Meehl et al.
470 2020).

471 Timeseries of mean length of dry spells in the dry season and mean length of wet spells in the
472 wet season for the NES region (Figure 7) show the same patterns of longer dry spells in the dry
473 season and shorter wet spells in the wet season. The dots at the top of each panel indicate when
474 the range of values in that year is statistically significantly different from the range over 1985-2014
475 and indicates the emergence of the signal from the noise. This suggests that the increase in the
476 mean length of dry spells in the dry season becomes statistically significantly different between
477 2020 and 2040 (depending on the emissions scenario) whereas the decrease in the mean length of
478 wet spells in the wet season is not statistically significant until 2060-2080 (timings are similar for
479 maximum spell lengths). These times of emergence are indicative, but may not be fully quantified,
480 as we have only used one ensemble member per model. For more robust times of emergence the
481 internal variability should be calculated using a large ensemble. For wet spells in the wet season
482 the change is less significant under the SSP245 scenario and diverges from the SSP585 scenario in
483 the 2060s (Figure 7b). The apparent jump in dry spell length around 2065 is not a model artefact,
484 but reflects the combination of internal variability and the levelling off of warming in the SSP245
485 scenario. Figure 7 also shows the large interannual variability in these metrics and the large model
486 spread. Two methodologies were used for calculating the timeseries; one using varying season

487 start and end dates and one using fixed seasons start and end dates (see methodology section 5).
488 The results shown in Figure 7 were the same for both methodologies, indicating the result is robust
489 and insensitive to changing season length. However, for the mean length of dry spells in the wet
490 season and mean length of wet spells in the dry season the signal (increase/decrease respectively)
491 becomes weaker and less statistically significant when varying onset is used (not shown). This
492 indicates that erroneously including parts of the other season when the time-invariant dates are
493 used can influence the calculation of these metrics, and indicates changes occurring in the margins
494 between the seasons.

495 2) AFRICA

496 Projected changes in the mean length of wet and dry spells are not consistent across the African
497 continent (Figure 8, Figure S17). While south-west Africa (SWAF) and south-east Africa (SEAF)
498 show longer dry spells in the dry season (increase in mean and maximum length), with median
499 increases in the maximum length greater than 20 days over SWAF, north-east Africa (NEAF) shows
500 shorter dry spells (median change in the maximum length of dry spells is a decrease of 12 days
501 under CMIP6 SSP585, Figure 8b-c). There is good model agreement in shorter dry season dry
502 spells over NEAF, with the 25th percentile below 0 for all scenarios. Pinto et al. (2016) also found
503 increases in CDD over Southern Africa, with increases of greater than 25 days over Zimbabwe and
504 Botswana, with larger increases under RCP8.5 than under RCP4.5, in agreement with Orłowsky
505 and Seneviratne (2012) and Sillmann et al. (2013b). Over East Africa previous studies report both
506 increases and decreases in dry spell lengths. Over southern Ethiopia, Tegegne et al. (2020) found a
507 decrease in CDD during the 2080s under RCP8.5, in agreement with the findings in Sillmann et al.
508 (2013b). However, Gudoshava et al. (2020) show only small changes (generally less than one day)
509 in CDD in March-May, June-September and October-December over the Horn of Africa; Ogega

510 et al. (2020) also found no large changes in CDD over Kenya and Uganda. Conversely, Osima
511 et al. (2018) find increasing CDD over the Horn of Africa. Our results here are consistent with
512 the studies of Sillmann et al. (2013b), Orlowsky and Seneviratne (2012) and Tegegne et al. (2020);
513 further detailed studies on this region should explore the range of projections from different studies,
514 taking into account the large variability in model projections over East Africa (Rowell et al. 2015).
515 West Africa (WAF) and Central Africa (CAF) show shorter dry spells in the future (Figure S17),
516 although the changes are smaller than those over NEAF and model agreement is weaker; Sillmann
517 et al. (2013b) show that changes in CDD are not significant over these regions.

518 Only two regions show notable changes in the length of wet spells in the wet season; WAF and
519 CAF show median decreases of 3-6 days in the maximum length of wet spells (under high emissions
520 scenarios, Figure 8d-e). Changes in the mean length also show decreases. While there is generally
521 good model agreement on shorter wet spells in the wet season over WAF and CAF (for the most part
522 the 25th percentile is below 0), there is a large range across the models, particularly under CMIP5
523 and over CAF. This may be related to poor model representation of the mean climate over this
524 region in CMIP5 models (Creese and Washington 2018) and to the inclusion of a wet-year-round
525 region in equatorial Africa. Klutse et al. (2018) also found a reduction in CWD in June-September
526 over West Africa, with reductions of up to four days over Nigeria and Guinea under 2°C of global
527 warming. Over central Africa Mba et al. (2018) found decreases in CWD in both March-May and
528 September-November.

529 Figure 9b shows that the decrease in the length of wet spells in the wet season over WAF becomes
530 statistically significantly different from 1985-2014 at around 2050 under SSP585. However, under
531 SSP245 the change does not become consistently statistically significantly different in the period
532 of this timeseries (up to 2100). For dry spells in the dry season over SEAF the increase in length
533 becomes statistically significantly different from 1985-2014 around 2040-2060, later than was

534 found for NES (Figure 9a). For dry spells in the dry season the scenarios diverge in the 2060s,
535 while for wet spells in the wet season the scenarios diverge in the 2040s.

536 3) ASIA

537 Generally, changes in the length of wet and dry spells are smaller and less significant, or exhibit
538 limited model consensus, over Asia. Figure 5 showed significant decreases in the mean length of
539 dry spells in the dry season over north-east China (also found by Han et al. 2018; Dong et al.
540 2020), but no other significant changes over this region. Figure 10b-c confirms that changes in
541 the length of dry spells in the dry season are generally small. The largest change is an increase of
542 four days in the maximum length of dry season dry spells over South Asia (SAS) under CMIP5
543 RCP8.5; this change is larger in CMIP5 than in CMIP6 (median in CMIP6 SSP585 is an increase
544 of one day), consistent with the slight increase in dry season rainfall over India found in CMIP6
545 SSP585, but little change in dry season rainfall found in CMIP5 RCP8.5. While there is an increase
546 in the maximum length of dry spells, the change in the mean length of dry spells is small (less
547 than 0.6 days), indicating that for the most part dry season dry spells are not getting longer. An
548 increase in the maximum, but not the mean also suggests an increase in the variability. This
549 highlights the importance of considering the mean as well as the maximum spell length. There is
550 limited model agreement in these changes. Han et al. (2018) also found little change in CDD over
551 South Asia and South East Asia in their analysis of CMIP5 models. Aadhar and Mishra (2020)
552 concluded that projections based on CMIP6 multi-model ensembles are not reliable over South
553 Asia as projections are different when the whole ensemble is used compared with just those models
554 that correctly represent current climate. Further work is required to investigate this region in more
555 detail.

556 Figure 10b-c also shows a slight increase in the maximum length of dry season dry spells over
557 south-east Asia (SEA). It should be noted that much of this region experiences a wet-year-round
558 rainfall regime, therefore only a small region (over Myanmar and Thailand) will be contributing to
559 this signal; this is supported by the findings of Ge et al. (2019), who show the largest increases in
560 CDD in the SEA region are over the Myanmar/Thailand peninsula. Figure 10b-c shows the median
561 changes are small (two and three days), and again, only seen in the maximum not the mean, with
562 limited model agreement.

563 Figure 10d-e shows changes in the length of wet spells in the wet season, with median decreases
564 in the maximum length of two and four days over SEA and little change in other regions. This
565 is consistent with a decrease in the number of wet season rainy days over this region. Again, the
566 change in the mean is small (less than 0.4 days), indicating only the longest wet spells are getting
567 shorter, not all wet spells, and also indicating a change in the variability. While Ge et al. (2019)
568 show increases in CWD in the CORDEX models over SEA, they also find that the increase is
569 larger under 1.5°C of global warming than under 2°C of global warming, and under 2°C of global
570 warming some regions show decreases (e.g. Borneo). 2°C of global warming is reached at around
571 2040 under SSP585 (O'Neill et al. 2016); therefore if the increased warming continues to decrease
572 the change in CWD, this is consistent with our finding of shorter wet spells. Over East Asia (EAS)
573 the changes are small, consistent with the results in Figure 5.

574 *e. Seasonal Maximum Temperature*

575 Interpreting agricultural implications of precipitation changes cannot be considered in isolation
576 from temperature, as the aridity or dryness over a region is determined by the difference between
577 supply (precipitation) and demand (measured by potential evapotranspiration (PET)) (Dai et al.
578 2018). Elevated greenhouse gas levels lead to increasing temperatures, which combined with small

579 changes in relative humidity, lead to large increases in the vapor pressure deficit and widespread
580 increases in PET (Dai et al. 2018). Zhao and Dai (2015) found that rising temperatures and vapor
581 deficits explain most of the projected ubiquitous global PET increase. On the other hand, elevated
582 CO₂ concentrations modify how vegetation responds to changing water availability through a
583 complex and uncertain combination of increased plant growth and increased water use efficiency
584 (Mankin et al. 2019; Peters et al. 2018; Kooperman et al. 2018). Furthermore, rainfall changes exert
585 a substantial influence on temperature changes since less cloud and rainfall increases absorbed solar
586 radiation while drier soils increase the sensible heat fraction. Therefore temperature responses in
587 wet and dry seasons are not expected to be uniform and are thus of considerable additional interest.

588 Figure 11 shows increasing temperatures across the tropics in both wet and dry seasons, as
589 projected under future climate change. Over northern South America, Southern Africa, and parts
590 of Asia, the increase in dry season maximum temperature is up to 3°C greater than the increase
591 in wet season maximum temperature (Figure 11a-b); Zhou et al. (2015) also found the largest
592 temperature increases over drier regions. In both northern South America and Southern Africa
593 this increase in dry season maximum temperature is combined with a decrease in dry season
594 rainfall (Figure 4b), which may lead to a substantial drying of soils during the dry season, affecting
595 perennial crops. Dai et al. (2018) found large increases in PET and decreases in soil moisture
596 over northern South America and southern Africa. Decreases in soil moisture across northern
597 South America and southern Africa were also reported by Collins et al. (2013) and Zhao and Dai
598 (2015). Furthermore, Zhao and Dai (2015) found decreases in soil moisture (hence increased
599 surface drying) in regions projected to receive higher precipitation amounts, due to fewer wet days
600 and longer dry spells and high temperatures, highlighting the importance of changes in frequency
601 in precipitation, in addition to changes in amount.

602 The contours on Figure 11 indicate that under the historical simulation over 1985-2014 only
603 northern Australia and the Sahel have mean seasonal maximum temperatures greater than 35°C
604 (dashed contour), whereas by the end of the 21st century under SSP585 parts of India, the Sahel,
605 northern South America and parts of northern Australia may all experience mean dry season
606 maximum temperatures of greater than 35°C (solid contour). This may have negative impacts on
607 crops including sorghum (FAO 2020). However, during the wet season temperatures are generally
608 less than 35°C, except over northern Australia and parts of the Sahel. This may mean that crops
609 grown during the wet season are less impacted by these elevated temperatures.

610 **4. Conclusions**

611 Changes in the mean and maximum lengths of wet and dry spells (and mean maximum tempera-
612 ture) have been calculated separately for the climatological wet and dry seasons using an ensemble
613 of CMIP5 and CMIP6 models across the global tropics and subtropics. An objective methodology
614 is used to classify the seasonality at each location and to determine the timing of the climatological
615 wet and dry season(s); metrics including total seasonal rainfall, number of rainy days, rain per
616 rainy day and the mean and maximum length of wet and dry spells are then calculated for the wet
617 and dry seasons separately.

618 Our main results are (also summarised in Figure 12):

- 619 • Onset of the annual wet season is projected to get later across South America, Southern Africa,
620 West Africa and the Sahel, with changes of up to two weeks. Over East Asia the onset is
621 projected to be earlier. Cessation of the annual wet season is projected to be later over the
622 Sahel, parts of Asia, and central America. These changes are consistent with the projected
623 global phase delay of the seasonal cycle of precipitation under future climate change (Dwyer
624 et al. 2014; Song et al. 2018).

- 625 • Changes in the mean and maximum length of dry spells are largest during the dry season.
626 Increasing dry season dry spell lengths were found over central America, north-east South
627 America, Southern Africa and Australia. Shorter dry spells in the dry season are found over
628 East Africa and parts of the Sahel, and East Asia. Changes in the length of dry spells in the
629 wet season are generally small, with only the Mediterranean and southern Europe showing
630 significant increases.
- 631 • Statistically significant decreases in the length of wet spells in the wet season are found over
632 Central and northern South America and West/Central Africa.
- 633 • For the most part, changes were of the same sign in CMIP5 and CMIP6, but of larger magnitude
634 under CMIP6, possibly related to the higher climatic sensitivity (Meehl et al. 2020).
- 635 • The time at which the change becomes statistically significantly different from the historical
636 period varies with metric and region; while the increase in length of dry spells in the dry season
637 over north-east South America is statistically significant around 2020-2040, the decrease in
638 the length of wet spells in the wet season over West Africa is not statistically significant until
639 around 2050. Times of emergence here are indicative; more robust times of emergence could
640 be calculated using a larger ensemble.
- 641 • Mean maximum temperature increases are greater for the dry season than for the wet season,
642 with mean maximum dry season temperatures increasing by up to 7°C, particularly over South
643 America, Southern Africa and parts of Asia. While only northern Australia is projected to
644 have large areas with mean maximum wet season temperatures >35°C at the end of the 21st
645 century under SSP585, northern South America, the Sahel, and India are projected to have
646 mean maximum dry season temperatures >35°C at the end of the 21st century under SSP585.

647 This paper aimed to address the question "Do changes in the length of wet and dry spells differ
648 in climatologically wet and dry seasons?". Here it has been decisively shown, considering both
649 the mean and maximum wet/dry spell lengths (thus considering all wet/dry spells, not just the
650 longest) that changes in the length of wet and dry spells are different in wet and dry seasons, and
651 that the increases in dry spell lengths expected under future climate change mostly occur during
652 the annual dry seasons. This has important implications for agriculture across the tropics, and
653 suggests that crops grown solely during the wet season may be less affected by longer dry spells
654 and increased water stress. However, for crops grown during the dry season and perennial crops,
655 longer dry spells in the dry season, combined with lower dry season rainfall and fewer dry season
656 rainy days may lead to elevated dry season water stress. This elevated dry season water stress
657 will be further exacerbated by increased evaporative demand due to higher temperatures; Scheff
658 and Frierson (2015) found aridification generally dominates over humidification in the tropics and
659 subtropics due to temperature-driven increases in potential evapotranspiration. Regions such as
660 central America, north-east South America, Southern Africa and Australia will be most impacted
661 by this. Further work, using detailed crop models, is required to determine the impacts on individual
662 crops.

663 Regional variations in the response of wet and dry spells to elevated greenhouse gas concen-
664 trations have been identified; the aim of this paper is to assess the changes in wet/dry season
665 precipitation characteristics and not to understand the regional changes in terms of circulation
666 change. Regional changes in rainfall across the tropics are driven by a range of factors including
667 changes in the Intertropical Convergence Zone (contraction, intensification and timing; Dwyer
668 et al. 2014; Su et al. 2017; Song et al. 2018) and subtropical drying, which is determined by
669 complex interplay between Hadley Cell expansion (Seidel et al. 2008; Scheff and Frierson 2012),
670 land ocean warming contrasts (Karnauskas and Ummenhofer 2014; He and Soden 2017), and

671 vegetation responses to elevated CO₂ (Mankin et al. 2018). Further work is required to understand
672 the changing regional/local circulations and energy and water fluxes that lead to these changes over
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References

- Aadhar, S., and V. Mishra, 2020: On the Projected Decline in Droughts Over South Asia in CMIP6 Multimodel Ensemble. *Journal of Geophysical Research: Atmospheres*, **125** (20), e2020JD033 587, doi:https://doi.org/10.1029/2020JD033587.
- Allan, R. P., and Coauthors, 2020: Advances in understanding large-scale responses of the water cycle to climate change. *Annals of the New York Academy of Sciences*, **1472** (1), 49–75.
- Allen, M. R., and W. J. Ingram, 2002: Constraints on future changes in climate and the hydrologic cycle. *Nature*, **419** (6903), 228–232.
- Avila-Diaz, A., V. Benezoli, F. Justino, R. Torres, and A. Wilson, 2020: Assessing current and future trends of climate extremes across Brazil based on reanalyses and earth system model projections. *Climate Dynamics*, **55** (5), 1403–1426.
- Barkhordarian, A., H. von Storch, A. Behrangi, P. C. Loikith, C. R. Mechoso, and J. Detzer, 2018: Simultaneous Regional Detection of Land-Use Changes and Elevated GHG Levels: The Case of Spring Precipitation in Tropical South America. *Geophysical Research Letters*, **45** (12), 6262–6271.
- Beck, H. E., E. F. Wood, M. Pan, C. K. Fisher, D. G. Miralles, A. I. J. M. van Dijk, T. R. McVicar, and R. F. Adler, 2019: MSWEP V2 Global 3-Hourly 0.1° Precipitation: Methodology and Quantitative Assessment. *Bulletin of the American Meteorological Society*, **100** (3), 473 – 500.
- Biasutti, M., and A. H. Sobel, 2009: Delayed Sahel rainfall and global seasonal cycle in a warmer climate. *Geophysical Research Letters*, **36** (23), L23 707.
- Brogli, R., S. L. Sørland, N. Kröner, and C. Schär, 2019: Causes of future Mediterranean precipitation decline depend on the season. *Environmental Research Letters*, **14** (11), 114 017.

- 716 Chou, C., J. C. H. Chiang, C.-W. Lan, C.-H. Chung, Y.-C. Liao, and C.-J. Lee, 2013: Increase in
717 the range between wet and dry season precipitation. *Nature Geoscience*, **6 (4)**, 263–267.
- 718 Collins, M., and Coauthors, 2013: Long-term climate change: projections, commitments and
719 irreversibility. *Climate Change 2013-The Physical Science Basis: Contribution of Working*
720 *Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*,
721 Cambridge University Press, 1029–1136.
- 722 Correa, I. C., P. A. Arias, and M. Rojas, 2020: Evaluation of multiple indices of the South American
723 monsoon. *International Journal of Climatology*, **41 (S1)**, E2801–E2819.
- 724 Creese, A., and R. Washington, 2018: A process-based assessment of CMIP5 rainfall in the Congo
725 Basin: the September–November rainy season. *Journal of Climate*, **31 (18)**, 7417–7439.
- 726 Dai, A., T. Zhao, and J. Chen, 2018: Climate change and drought: A precipitation and evaporation
727 perspective. *Current Climate Change Reports*, **4 (3)**, 301–312.
- 728 Deng, S., C. Sheng, N. Yang, L. Song, and Q. Huang, 2020: Anthropogenic forcing enhances
729 rainfall seasonality in global land monsoon regions. *Environmental Research Letters*, **15 (10)**,
730 104 057.
- 731 Dong, G., Z. Jiang, Z. Tian, E. Buonomo, L. Sun, and D. Fan, 2020: Projecting Changes in Mean
732 and Extreme Precipitation Over Eastern China During 2041–2060. *Earth and Space Science*,
733 **7 (9)**, e2019EA001 024.
- 734 Dunning, C. M., R. P. Allan, and E. Black, 2017: Identification of deficiencies in seasonal rainfall
735 simulated by CMIP5 climate models. *Environmental Research Letters*, **12 (11)**, 114 001.
- 736 Dunning, C. M., E. Black, and R. P. Allan, 2018: Later wet seasons with more intense rainfall over
737 Africa under future climate change. *Journal of Climate*, **31 (23)**, 9719–9738.

738 Dunning, C. M., E. C. Black, and R. P. Allan, 2016: The onset and cessation of seasonal rainfall
739 over Africa. *Journal of Geophysical Research: Atmospheres*, **121** (19), 11,405– 11,424.

740 Dwyer, J. G., M. Biasutti, and A. H. Sobel, 2014: The Effect of Greenhouse Gas–Induced Changes
741 in SST on the Annual Cycle of Zonal Mean Tropical Precipitation. *Journal of Climate*, **27** (12),
742 4544–4565.

743 Eekhout, J. P. C., J. E. Hunink, W. Terink, and J. de Vente, 2018: Why increased extreme
744 precipitation under climate change negatively affects water security. *Hydrology and Earth System
745 Sciences*, **22** (11), 5935–5946.

746 Espinoza, J. C., J. Ronchail, J. A. Marengo, and H. Segura, 2019: Contrasting North–South
747 changes in Amazon wet-day and dry-day frequency and related atmospheric features (1981–
748 2017). *Climate Dynamics*, **52** (9-10), 5413–5430.

749 Eyring, V., S. Bony, G. A. Meehl, C. A. Senior, B. Stevens, R. J. Stouffer, and K. E. Taylor, 2016:
750 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design
751 and organization. *Geoscientific Model Development*, **9** (5), 1937–1958.

752 FAO, 2020: Crop information: Sorghum (accessed 2020-12-01). URL [http://www.fao.org/
753 land-water/databases-and-software/crop-information/sorghum/en/](http://www.fao.org/land-water/databases-and-software/crop-information/sorghum/en/).

754 Feng, X., A. Porporato, and I. Rodriguez-Iturbe, 2013: Changes in rainfall seasonality in the
755 tropics. *Nature Climate Change*, **3** (9), 811–815.

756 Funk, C., L. Harrison, L. Alexander, P. Peterson, A. Behrangi, and G. Husak, 2019: Exploring
757 trends in wet-season precipitation and drought indices in wet, humid and dry regions. *Environ-
758 mental Research Letters*, **14** (11), 115 002.

- 759 Funk, C., and Coauthors, 2015: The climate hazards infrared precipitation with stations—a new
760 environmental record for monitoring extremes. *Scientific Data*, **2** (1), 1–21.
- 761 Ge, F., and Coauthors, 2019: Risks of precipitation extremes over Southeast Asia: does 1.5° C or
762 2° C global warming make a difference? *Environmental Research Letters*, **14** (4), 044 015.
- 763 Giorgi, F., E. Coppola, and F. Raffaele, 2014: A consistent picture of the hydroclimatic response
764 to global warming from multiple indices: Models and observations. *Journal of Geophysical
765 Research: Atmospheres*, **119** (20), 11 695–11 708.
- 766 Giorgi, F., E.-S. Im, E. Coppola, N. Diffenbaugh, X. Gao, L. Mariotti, and Y. Shi, 2011: Higher
767 hydroclimatic intensity with global warming. *Journal of Climate*, **24** (20), 5309–5324.
- 768 Giorgi, F., F. Raffaele, and E. Coppola, 2019: The response of precipitation characteristics to
769 global warming from climate projections. *Earth System Dynamics*, **10** (1), 73–89.
- 770 Gudoshava, M., and Coauthors, 2020: Projected effects of 1.5 C and 2 C global warming levels
771 on the intra-seasonal rainfall characteristics over the Greater Horn of Africa. *Environmental
772 Research Letters*, **15** (3), 034 037.
- 773 Ha, K.-J., S. Moon, A. Timmermann, and D. Kim, 2020: Future changes of summer monsoon
774 characteristics and evaporative demand over Asia in CMIP6 simulations. *Geophysical Research
775 Letters*, **47** (8), e2020GL087 492.
- 776 Han, T., H. Chen, X. Hao, and H. Wang, 2018: Projected changes in temperature and precipitation
777 extremes over the Silk Road Economic Belt regions by the Coupled Model Intercomparison
778 Project Phase 5 multi-model ensembles. *International Journal of Climatology*, **38** (11), 4077–
779 4091.

780 He, C., T. Li, and W. Zhou, 2020: Drier North American Monsoon in Contrast to Asian–African
781 Monsoon under Global Warming. *Journal of Climate*, **33 (22)**, 9801–9816.

782 He, J., and B. J. Soden, 2017: A re-examination of the projected subtropical precipitation decline.
783 *Nature Climate Change*, **7 (1)**, 53–57.

784 Held, I. M., and B. J. Soden, 2006: Robust Responses of the Hydrological Cycle to Global
785 Warming. *Journal of Climate*, **19 (21)**, 5686–5699.

786 Herrmann, S. M., and K. I. Mohr, 2011: A continental-scale classification of rainfall seasonality
787 regimes in Africa based on gridded precipitation and land surface temperature products. *Journal*
788 *of Applied Meteorology and Climatology*, **50 (12)**, 2504–2513.

789 Iturbide, M., and Coauthors, 2020: An update of IPCC climate reference regions for subcontinental
790 analysis of climate model data: Definition and aggregated datasets. *Earth System Science Data*,
791 **12 (4)**, 2959–2970.

792 Karnauskas, K. B., and C. C. Ummenhofer, 2014: On the dynamics of the Hadley circulation and
793 subtropical drying. *Climate Dynamics*, **42 (9-10)**, 2259–2269.

794 Kitoh, A., H. Endo, K. Krishna Kumar, I. F. Cavalcanti, P. Goswami, and T. Zhou, 2013: Monsoons
795 in a changing world: a regional perspective in a global context. *Journal of Geophysical Research:*
796 *Atmospheres*, **118 (8)**, 3053–3065.

797 Klutse, N. A. B., and Coauthors, 2018: Potential impact of 1.5 C and 2 C global warming
798 on consecutive dry and wet days over West Africa. *Environmental Research Letters*, **13 (5)**,
799 055 013.

800 Kooperman, G. J., M. D. Fowler, F. M. Hoffman, C. D. Koven, K. Lindsay, M. S. Pritchard, A. L.
801 Swann, and J. T. Randerson, 2018: Plant physiological responses to rising CO₂ modify simulated

802 daily runoff intensity with implications for global-scale flood risk assessment. *Geophysical*
803 *Research Letters*, **45 (22)**, 12–457.

804 Kumar, S., R. P. Allan, F. Zwiers, D. M. Lawrence, and P. A. Dirmeyer, 2015: Revisiting trends
805 in wetness and dryness in the presence of internal climate variability and water limitations over
806 land. *Geophysical Research Letters*, **42 (24)**, 10,867–10,875.

807 Lan, C.-W., M.-H. Lo, C.-A. Chen, and J.-Y. Yu, 2019: The mechanisms behind changes in the
808 seasonality of global precipitation found in reanalysis products and CMIP5 simulations. *Climate*
809 *Dynamics*, **53 (7-8)**, 4173–4187.

810 Lau, W. K.-M., H.-T. Wu, and K.-M. Kim, 2013: A canonical response of precipitation char-
811 acteristics to global warming from CMIP5 models. *Geophysical Research Letters*, **40 (12)**,
812 3163–3169.

813 Liebmann, B., I. Bladé, G. N. Kiladis, L. M. Carvalho, G. B. Senay, D. Allured, S. Leroux, and
814 C. Funk, 2012: Seasonality of African precipitation from 1996 to 2009. *Journal of Climate*,
815 **25 (12)**, 4304–4322.

816 Mankin, J. S., R. Seager, J. E. Smerdon, B. I. Cook, and A. P. Williams, 2019: Mid-latitude
817 freshwater availability reduced by projected vegetation responses to climate change. *Nature*
818 *Geoscience*, **12 (12)**, 983–988.

819 Mankin, J. S., R. Seager, J. E. Smerdon, B. I. Cook, A. P. Williams, and R. M. Horton, 2018:
820 Blue water trade-offs with vegetation in a CO₂-enriched climate. *Geophysical Research Letters*,
821 **45 (7)**, 3115–3125.

822 Marvel, K., M. Biasutti, C. Bonfils, K. E. Taylor, Y. Kushnir, and B. I. Cook, 2017: Observed and
823 Projected Changes to the Precipitation Annual Cycle. *Journal of Climate*, **30 (13)**, 4983–4995.

824 Mba, W. P., and Coauthors, 2018: Consequences of 1.5 C and 2 C global warming levels for
825 temperature and precipitation changes over Central Africa. *Environmental Research Letters*,
826 **13 (5)**, 055 011.

827 Meehl, G. A., C. A. Senior, V. Eyring, G. Flato, J.-F. Lamarque, R. J. Stouffer, K. E. Taylor, and
828 M. Schlund, 2020: Context for interpreting equilibrium climate sensitivity and transient climate
829 response from the CMIP6 Earth system models. *Science Advances*, **6 (26)**, eaba1981.

830 Ogega, O. M., J. Koske, J. B. Kung'u, E. Scoccimarro, H. S. Endris, and M. N. Mistry, 2020:
831 Heavy precipitation events over East Africa in a changing climate: results from CORDEX
832 RCMs. *Climate Dynamics*, **55**, 993–1009.

833 O'Neill, B. C., and Coauthors, 2016: The Scenario Model Intercomparison Project (ScenarioMIP)
834 for CMIP6. *Geoscientific Model Development*, **9 (9)**, 3461–3482.

835 Orłowsky, B., and S. I. Seneviratne, 2012: Global changes in extreme events: regional and seasonal
836 dimension. *Climatic Change*, **110 (3-4)**, 669–696.

837 Osima, S., and Coauthors, 2018: Projected climate over the Greater Horn of Africa under 1.5 C
838 and 2 C global warming. *Environmental Research Letters*, **13 (6)**, 065 004.

839 Parsons, L., 2020: Implications of CMIP6 projected drying trends for 21st century Amazonian
840 drought risk. *Earth's Future*, **8 (10)**, e2020EF001 608.

841 Pascale, S., V. Lucarini, X. Feng, A. Porporato, and S. ul Hasson, 2016: Projected changes
842 of rainfall seasonality and dry spells in a high greenhouse gas emissions scenario. *Climate*
843 *Dynamics*, 1410.3116.

844 Peters, W., and Coauthors, 2018: Increased water-use efficiency and reduced CO₂ uptake by plants
845 during droughts at a continental scale. *Nature Geoscience*, **11 (10)**, 744–748.

846 Pinto, I., C. Lennard, M. Tadross, B. Hewitson, A. Dosio, G. Nikulin, H.-J. Panitz, and M. E.
847 Shongwe, 2016: Evaluation and projections of extreme precipitation over southern Africa from
848 two CORDEX models. *Climatic Change*, **135 (3-4)**, 655–668.

849 Polade, S. D., D. W. Pierce, D. R. Cayan, A. Gershunov, and M. D. Dettinger, 2014: The key role
850 of dry days in changing regional climate and precipitation regimes. *Scientific Reports*, **4**, 4364.

851 Polson, D., and G. Hegerl, 2017: Strengthening contrast between precipitation in tropical wet and
852 dry regions. *Geophysical Research Letters*, **44 (1)**, 365–373.

853 Richardson, T., and Coauthors, 2018: Carbon dioxide physiological forcing dominates projected
854 eastern Amazonian drying. *Geophysical Research Letters*, **45 (6)**, 2815–2825.

855 Rockström, J., and Coauthors, 2010: Managing water in rainfed agriculture—The need for a
856 paradigm shift. *Agricultural Water Management*, **97 (4)**, 543–550.

857 Rowell, D. P., B. B. Booth, S. E. Nicholson, and P. Good, 2015: Reconciling past and future rainfall
858 trends over East Africa. *Journal of Climate*, **28 (24)**, 9768–9788.

859 Scheff, J., and D. M. Frierson, 2012: Robust future precipitation declines in CMIP5 largely reflect
860 the poleward expansion of model subtropical dry zones. *Geophysical Research Letters*, **39**,
861 L18 704.

862 Scheff, J., and D. M. Frierson, 2015: Terrestrial aridity and its response to greenhouse warming
863 across CMIP5 climate models. *Journal of Climate*, **28 (14)**, 5583–5600.

864 Schurer, A. P., A. P. Ballinger, A. R. Friedman, and G. C. Hegerl, 2020: Human influence
865 strengthens the contrast between tropical wet and dry regions. *Environmental Research Letters*,
866 **15 (10)**, 104 026.

- 867 Schwalm, C. R., S. Glendon, and P. B. Duffy, 2020: RCP8.5 tracks cumulative CO2 emissions.
868 *Proceedings of the National Academy of Sciences*, **117 (33)**, 19 656–19 657.
- 869 Seidel, D. J., Q. Fu, W. J. Randel, and T. J. Reichler, 2008: Widening of the tropical belt in a
870 changing climate. *Nature Geoscience*, **1 (1)**, 21–24.
- 871 Seneviratne, S., and Coauthors, 2012: Changes in climate extremes and their impacts on the natural
872 physical environment. *Managing the risks of extreme events and disasters to advance climate*
873 *change adaptation*, A Special Report of Working Groups I and II of the Intergovernmental Panel
874 on Climate Change (IPCC). Cambridge University Press Cambridge, UK, and New York, NY,
875 USA, 109–230.
- 876 Seth, A., S. A. Rauscher, M. Biasutti, A. Giannini, S. J. Camargo, and M. Rojas, 2013: CMIP5
877 Projected Changes in the Annual Cycle of Precipitation in Monsoon Regions. *Journal of Climate*,
878 **26 (19)**, 7328–7351.
- 879 Sillmann, J., V. Kharin, X. Zhang, F. Zwiers, and D. Bronaugh, 2013a: Climate extremes indices
880 in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. *Journal of*
881 *Geophysical Research: Atmospheres*, **118 (4)**, 1716–1733.
- 882 Sillmann, J., V. V. Kharin, F. Zwiers, X. Zhang, and D. Bronaugh, 2013b: Climate extremes indices
883 in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *Journal of Geophysical*
884 *Research: Atmospheres*, **118 (6)**, 2473–2493.
- 885 Small, R. J. O., S. P. de Szoeko, and S.-P. Xie, 2007: The Central American Midsummer Drought:
886 Regional Aspects and Large-Scale Forcing. *Journal of Climate*, **20 (19)**, 4853 – 4873.
- 887 Song, F., L. R. Leung, J. Lu, and L. Dong, 2018: Seasonally dependent responses of subtropical
888 highs and tropical rainfall to anthropogenic warming. *Nature Climate Change*, **8 (9)**, 787–792.

- 889 Su, H., and Coauthors, 2017: Tightening of tropical ascent and high clouds key to precipitation
890 change in a warmer climate. *Nature Communications*, **8**, 15 771.
- 891 Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment
892 design. *Bulletin of the American Meteorological Society*, **93 (4)**, 485–498.
- 893 Tegegne, G., A. M. Melesse, and T. Alamirew, 2020: Projected changes in extreme precipitation
894 indices from CORDEX simulations over Ethiopia, East Africa. *Atmospheric Research*, **247**,
895 105 156.
- 896 Trenberth, K. E., 2011: Changes in precipitation with climate change. *Climate Research*, **47 (1-2)**,
897 123–138.
- 898 Van Vuuren, D. P., and Coauthors, 2011: The representative concentration pathways: an overview.
899 *Climatic Change*, **109 (1-2)**, 5.
- 900 Wang, B., C. Jin, and J. Liu, 2020: Understanding future change of global monsoons projected by
901 CMIP6 models. *Journal of Climate*, **33 (15)**, 6471–6489.
- 902 Wang, B., and Coauthors, 2021: Monsoons climate change assessment. *Bulletin of the American*
903 *Meteorological Society*, **102 (1)**, E1–E19.
- 904 Yang, W., R. Seager, M. A. Cane, and B. Lyon, 2015: The Annual Cycle of East African Precipi-
905 tation. *Journal of Climate*, **28 (6)**, 2385–2404.
- 906 Yin, J., P. Gentine, S. Zhou, S. C. Sullivan, R. Wang, Y. Zhang, and S. Guo, 2018: Large
907 increase in global storm runoff extremes driven by climate and anthropogenic changes. *Nature*
908 *Communications*, **9 (1)**, 1–10.

- 909 Zhang, X., L. Alexander, G. C. Hegerl, P. Jones, A. K. Tank, T. C. Peterson, B. Trewin, and
910 F. W. Zwiers, 2011: Indices for monitoring changes in extremes based on daily temperature and
911 precipitation data. *Wiley Interdisciplinary Reviews: Climate Change*, **2 (6)**, 851–870.
- 912 Zhao, T., and A. Dai, 2015: The magnitude and causes of global drought changes in the twenty-first
913 century under a low–moderate emissions scenario. *Journal of climate*, **28 (11)**, 4490–4512.
- 914 Zhou, L., H. Chen, and Y. Dai, 2015: Stronger warming amplification over drier ecoregions
915 observed since 1979. *Environmental Research Letters*, **10 (6)**, 064012.

916 **LIST OF FIGURES**

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 943 compared with the historical simulation over 1985-2014. Stippling indicates where 60% of
 944 the models show a statistically significant change (t-test, 10% significance level) of the same
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 955 whiskers extend from the first datum greater than Q1 minus 1.5 times the interquartile range
 956 to the last datum less than Q3 plus 1.5 times the interquartile range - values outside this range
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 964 Mann–Whitney U and t test. 51

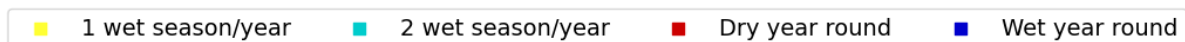
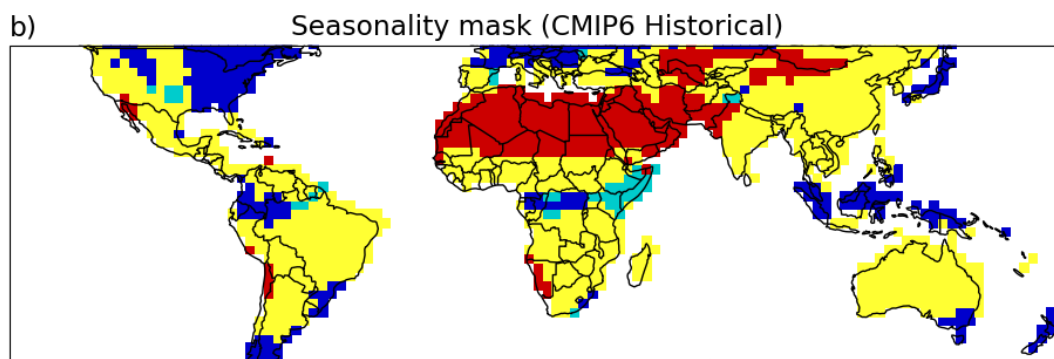
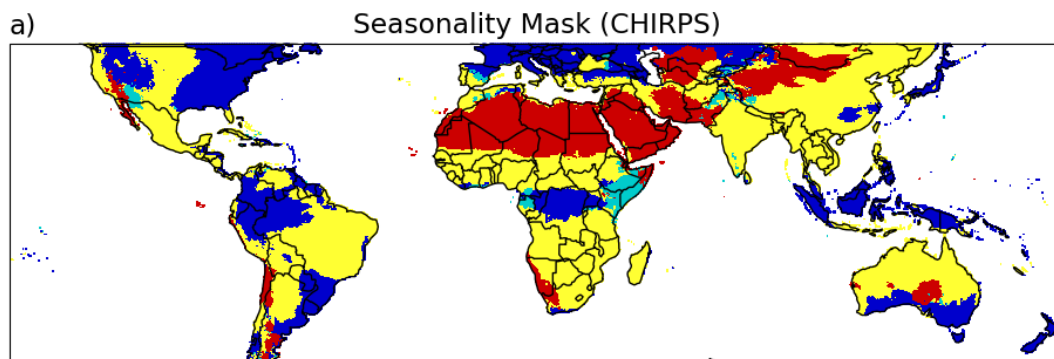
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 976 the shading indicates one standard deviation. The dots indicate when the range of values
 977 from 18 models for that year is significantly different from the range for 1985–2014 at the
 978 5% level, using a Mann–Whitney U and t test. 53

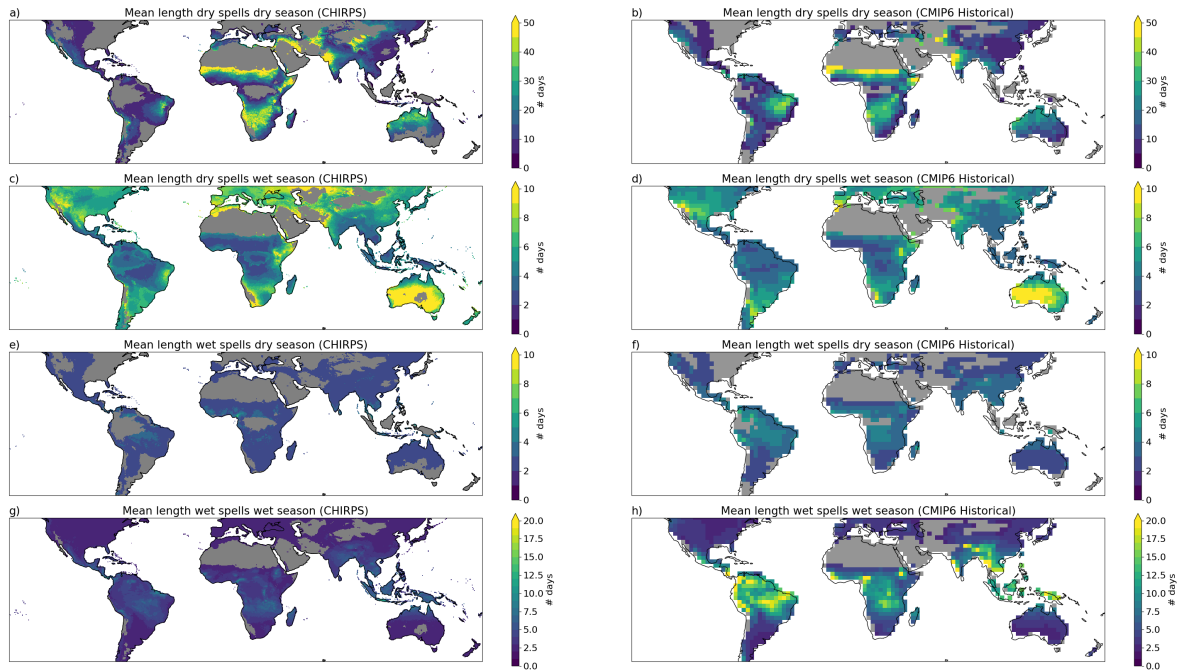
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 982 wet season. The different colours indicate the CMIP era (CMIP5 or CMIP6) and scenario
 983 (SSP 245, SSP 585, RCP 4.5, RCP 8.5). For all boxplots the change is computed from the
 984 historical simulation for 1985–2014 to the select scenario for 2070–2099. 54

985 **Fig. 11.** CMIP6 multi-model median change in a) mean wet season maximum daily temperature
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 988 the CMIP6 multi-model median wet and dry season mean daily maximum temperature is
 989 greater than 35°C for the historical simulation over 1985–2014 (dashed line) and the SSP585
 990 simulation over 2070–2099 (solid line). In all panels grey regions indicate where at least
 991 50% of the models do not give a value (dry year round or wet year round in the dry season
 992 plots). 55

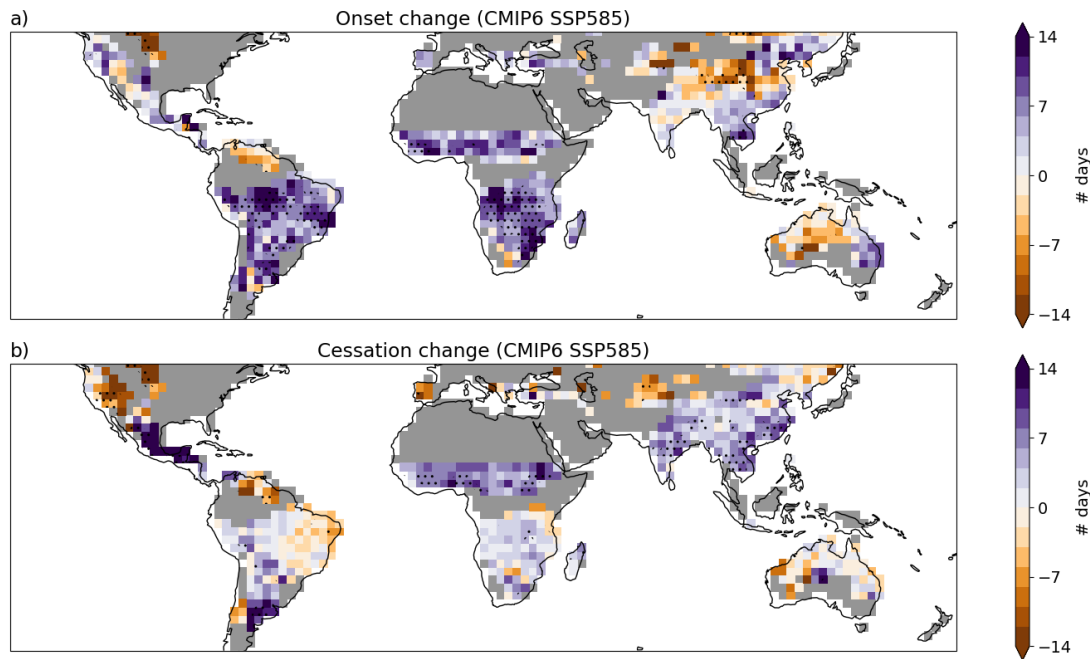
993 **Fig. 12.** Schematic summarising the changes in wet/dry season rainfall and wet/dry spell lengths in
 994 wet/dry seasons found here; the top panel is for dry seasons and the bottom row is for wet
 995 seasons (including regions that are wet year round).
 996 (Top) Longer dry spells and lower rainfall during the dry season are found over Central and
 997 South America and Southern Africa. Shorter dry spells and more rainfall during the dry
 998 season are found over East Africa and parts of Asia and the Sahel.
 999 (Bottom) More rainfall in the wet season is found over East Africa and Asia. Less rainfall in
 1000 the wet season is found over northern South America. Reductions in the length of wet spells
 1001 in the wet season are found over South America and West and Central Africa. 56



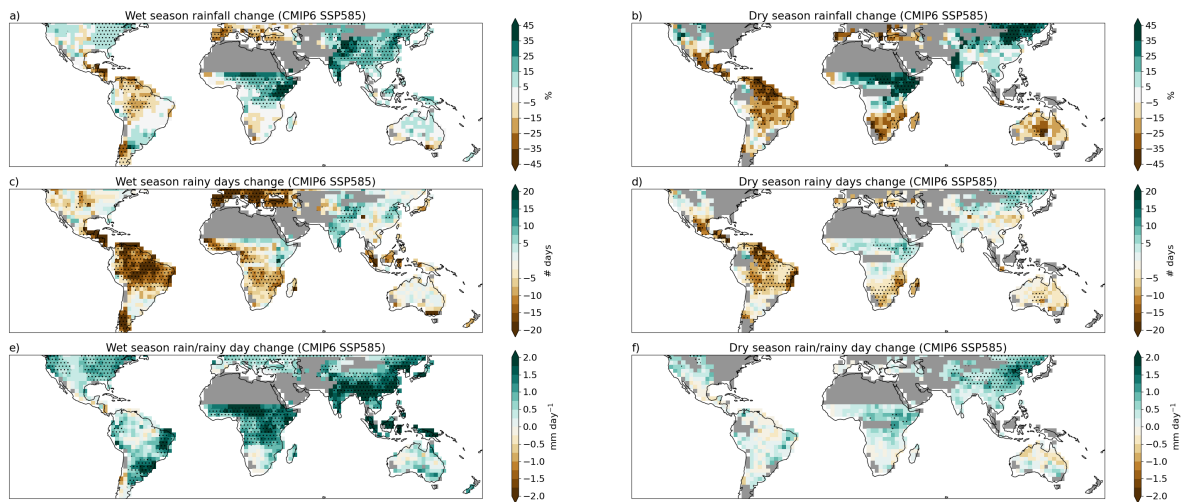
1002 FIG. 1. a) Seasonality mask produced using CHIRPS rainfall data over 1985-2014. b) CMIP6 multi-model
 1003 modal seasonality mask for the historical simulation over 1985-2014. Red indicates dry-year-round, blue indicates
 1004 wet-year-round, yellow indicates one wet season per year and green indicates two wet seasons per year. See
 1005 Figure S1 for CMIP5 and other scenarios.



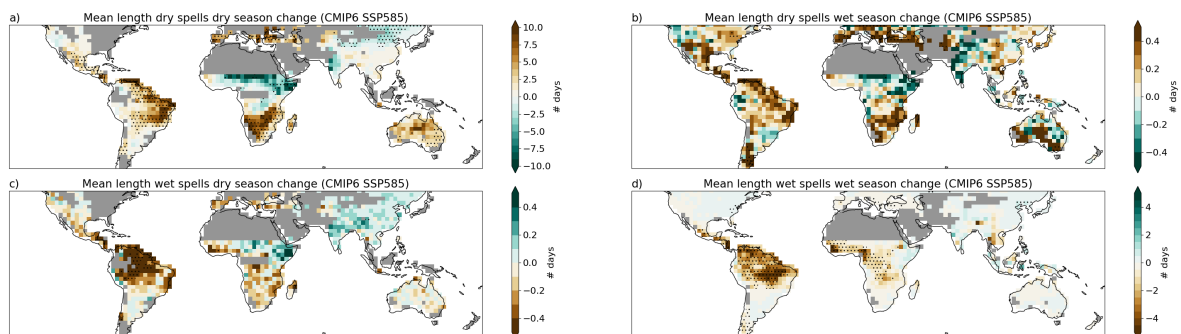
1006 FIG. 2. Mean length of a-b) dry spells in the dry season, c-d) dry spells in the wet season, e-f) wet spells in
 1007 the dry season and g-h) wet spells in the wet season from CHIRPS (a,c,e,g) and the multi-model median of the
 1008 CMIP6 historical simulations (b,d,f,h). 1985-2014 is used for both CHIRPS and CMIP6. Grey regions indicate
 1009 where at least 50% of the models do not give a value (dry year round or wet year round in the dry season plots),
 1010 or where CHIRPS is wet year round or dry year round.



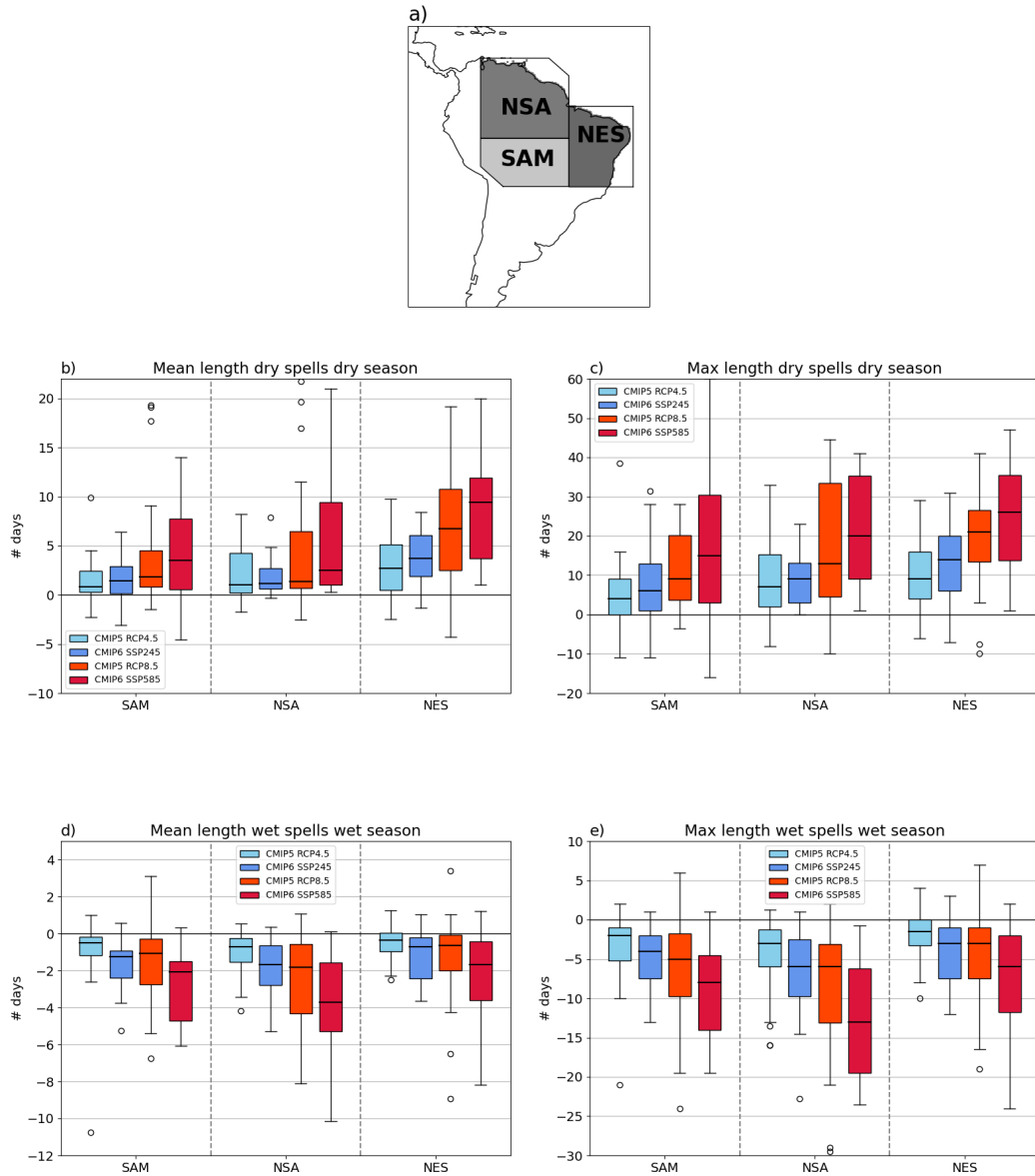
1011 FIG. 3. CMIP6 multi-model median change in a) onset of the annual wet season and b) cessation of the annual
 1012 wet season for the SSP585 scenario over 2070-2099 compared with the historical simulation over 1985-2014.
 1013 Purple indicates later while orange indicates earlier. Stippling indicates where 75% of the models agree on
 1014 the sign of the median. Grey regions indicate where at least 50% of the models do not give a value (dry year
 1015 round/wet year round/ biannual regime).



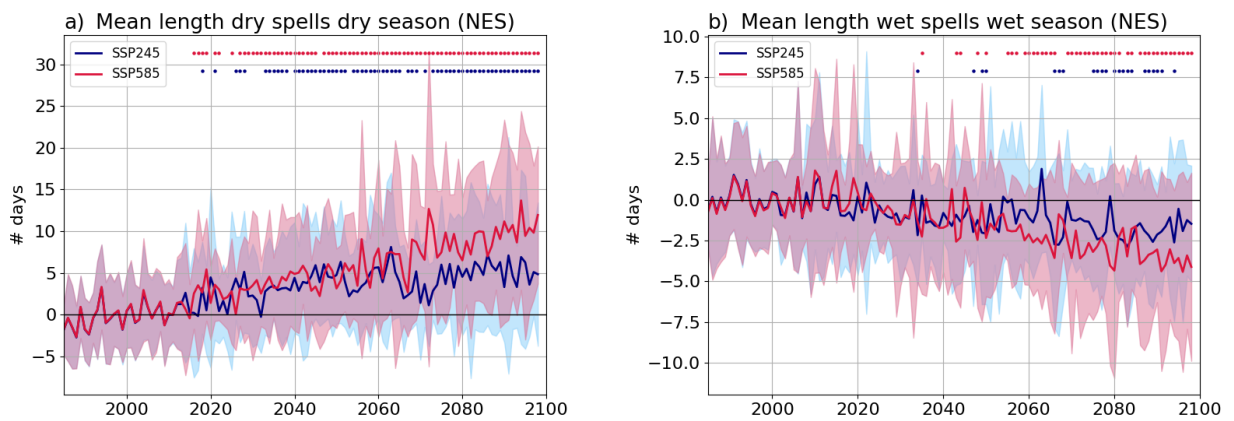
1016 FIG. 4. CMIP6 multi-model median change in a) wet season rainfall, b) dry season rainfall, c) number of
 1017 rainy days in the wet season, d) number of rainy days in the dry season, e) wet season rain per rainy day and f)
 1018 dry season rain per rainy day for the SSP585 scenario over 2070-2099 compared with the historical simulation
 1019 over 1985-2014. Stippling indicates where 60% of the models show a statistically significant change (t-test, 10%
 1020 significance level) of the same sign as the median change. Grey regions indicate where at least 50% of the models
 1021 do not give a value (dry year round or wet year round in the dry season plots).



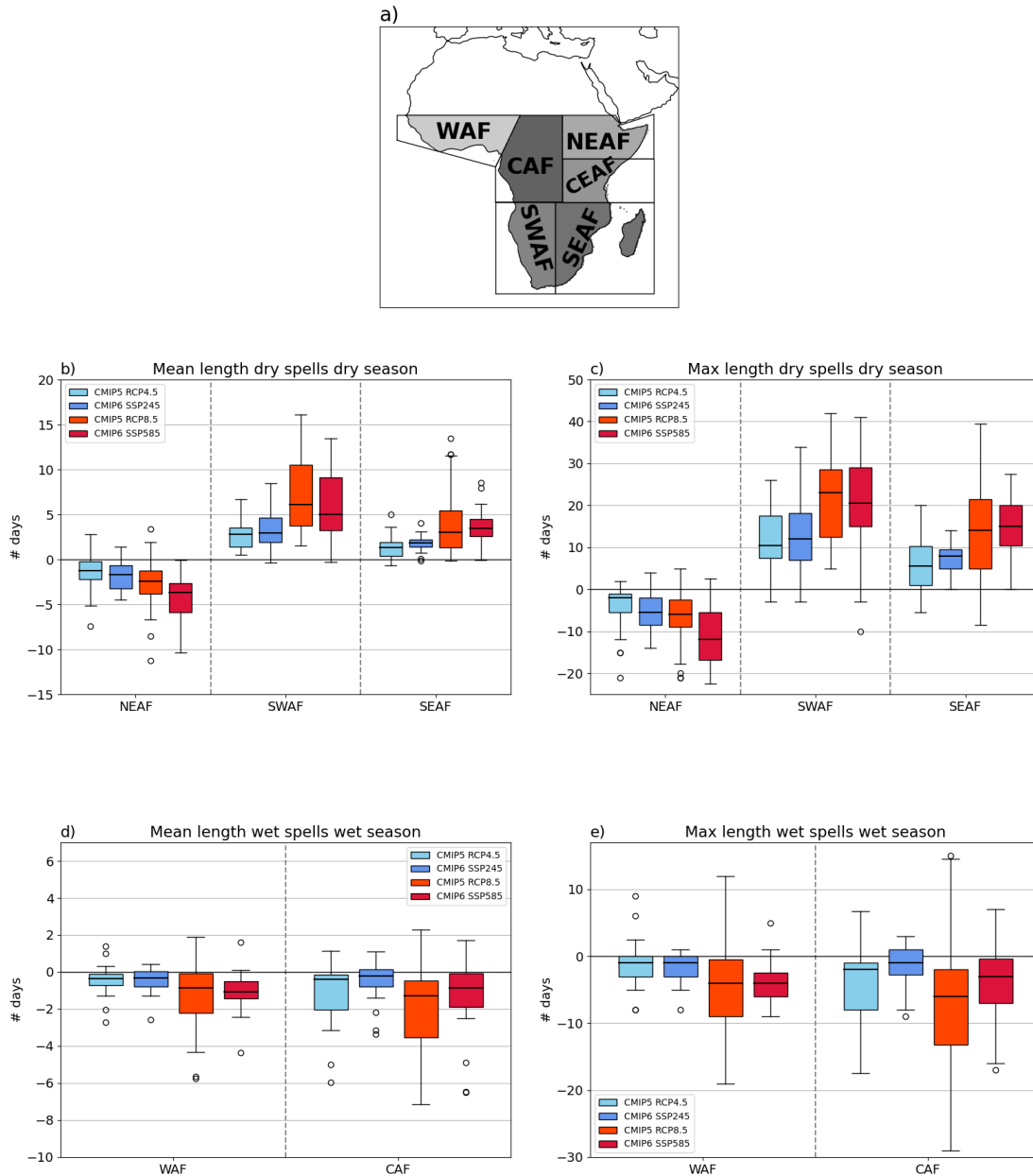
1022 FIG. 5. CMIP6 multi-model median change in a) mean length of dry spells in the dry season, b) mean length
 1023 of dry spells in the wet season, c) mean length of wet spells in the dry season, and d) mean length of wet spells in
 1024 the wet season for the SSP585 scenario over 2070-2099 compared with the historical simulation over 1985-2014.
 1025 Stippling indicates where 60% of the models show a statistically significant change (t-test, 10% significance
 1026 level) of the same sign as the median change. Grey regions indicate where at least 50% of the models do not give
 1027 a value (dry year round or wet year round in the dry season plots).



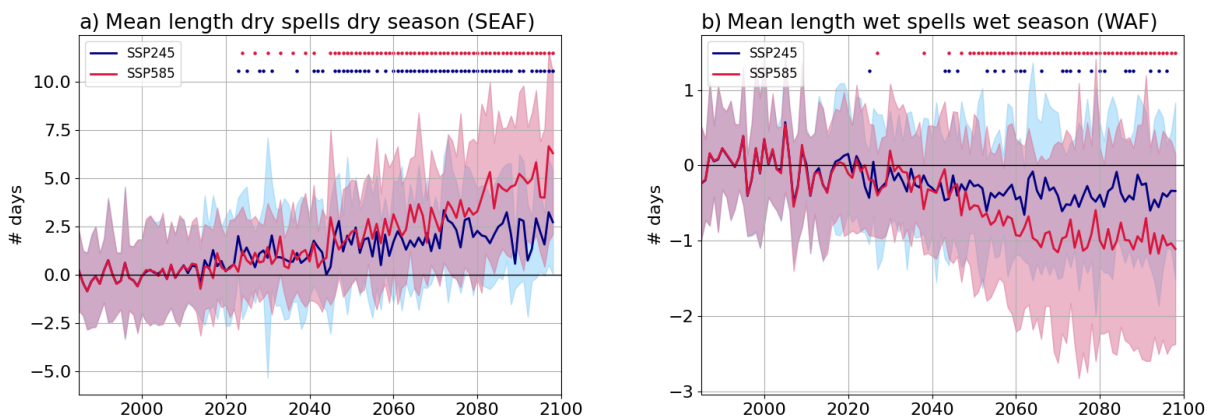
1028 FIG. 6. a) Region map showing the location of South American Monsoon (SAM), north South America (NSA)
 1029 and north-east South America (NES). b-c) Boxplots showing the change in mean/max length of dry spells in the
 1030 dry season and d-e) boxplots showing the change in mean/max length of wet spells in the wet season over SAM,
 1031 NSA, and NES. The different colours indicate the CMIP era (CMIP5 or CMIP6) and scenario (SSP 245, SSP
 1032 585, RCP 4.5, RCP 8.5). For all boxplots the change is computed from the historical simulation for 1985-2014
 1033 to the select scenario for 2070-2099. The box extends from the lower quartile (Q1) to the upper quartile (Q3)
 1034 of the data and the line in the middle shows the median. The whiskers extend from the first datum greater than
 1035 Q1 minus 1.5 times the interquartile range to the last datum less than Q3 plus 1.5 times the interquartile range
 1036 - values outside this range are considered to be outliers and marked with a circle. The same is the case for all
 1037 boxplots in this paper.



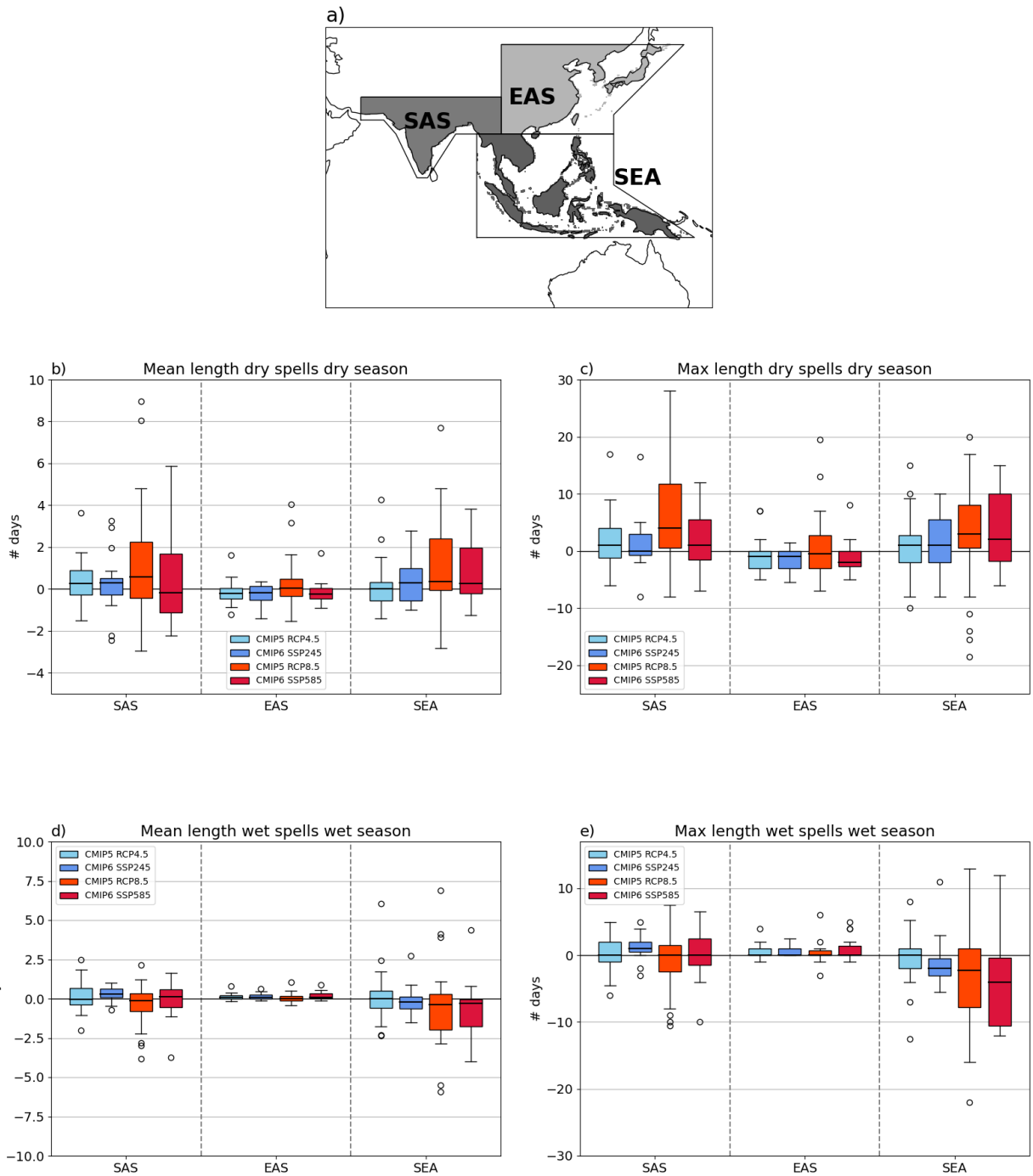
1038 FIG. 7. Timeseries of a) mean length of dry spells in the dry season and b) mean length of wet spells in the wet
 1039 season for the north-east South America region. The blue/red line shows the multi-model mean over the CMIP6
 1040 models for the SSP245/SSP585 scenario; the shading indicates one standard deviation. The dots indicate when
 1041 the range of values from 18 models for that year is significantly different from the range for 1985–2014 at the 5%
 1042 level, using a Mann–Whitney U and t test.



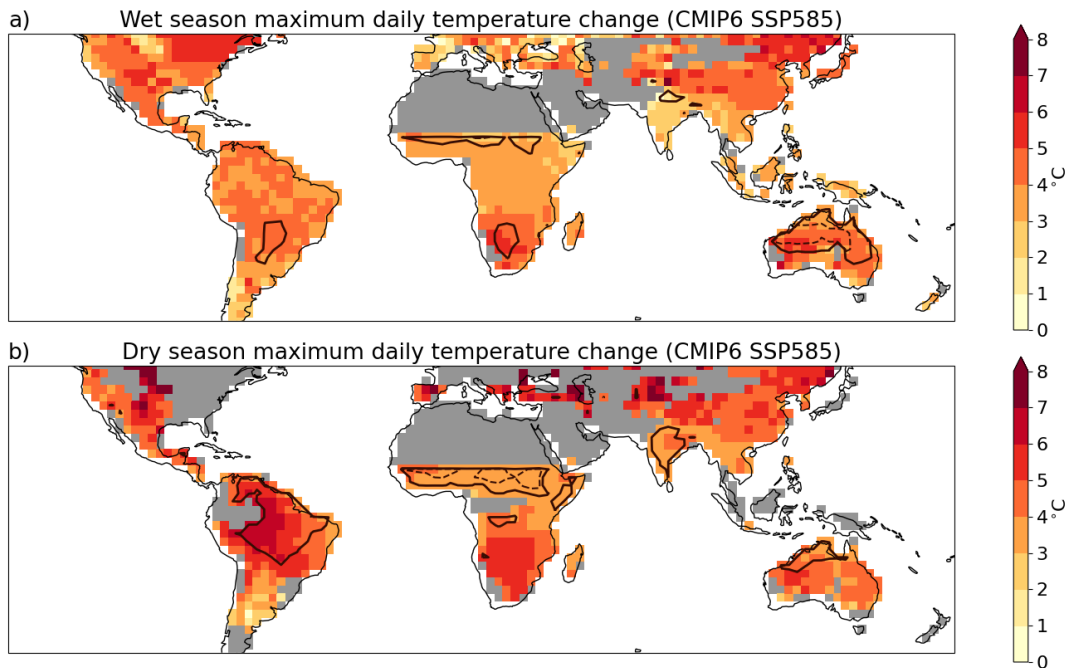
1043 FIG. 8. a) Region map showing the location of West Africa (WAF), Central Africa (CAF), North East Africa
 1044 (NEAF), Central East Africa (CEAF), South West Africa (SWAF), and South East Africa (SEAF). b-c) Boxplots
 1045 showing the change in mean/max length of dry spells in the dry season over NEAF, SWAF and SEAF. d-e)
 1046 Boxplots showing mean/max length of wet spells in the wet season over WAF and CAF. The different colours
 1047 indicate the CMIP era (CMIP5 or CMIP6) and scenario (SSP 245, SSP 585, RCP 4.5, RCP 8.5). For all boxplots
 1048 the change is computed from the historical simulation for 1985-2014 to the select scenario for 2070-2099. Results
 1049 for all regions are shown in Figure S17.



1050 FIG. 9. Timeseries of a) mean length of dry spells in the dry season over south-east Africa (SEAF) and b)
 1051 mean length of wet spells in the wet season over West Africa (WAF). The blue/red line shows the multi-model
 1052 mean over the CMIP6 models for the SSP245/SSP585 scenario; the shading indicates one standard deviation.
 1053 The dots indicate when the range of values from 18 models for that year is significantly different from the range
 1054 for 1985–2014 at the 5% level, using a Mann–Whitney U and t test.

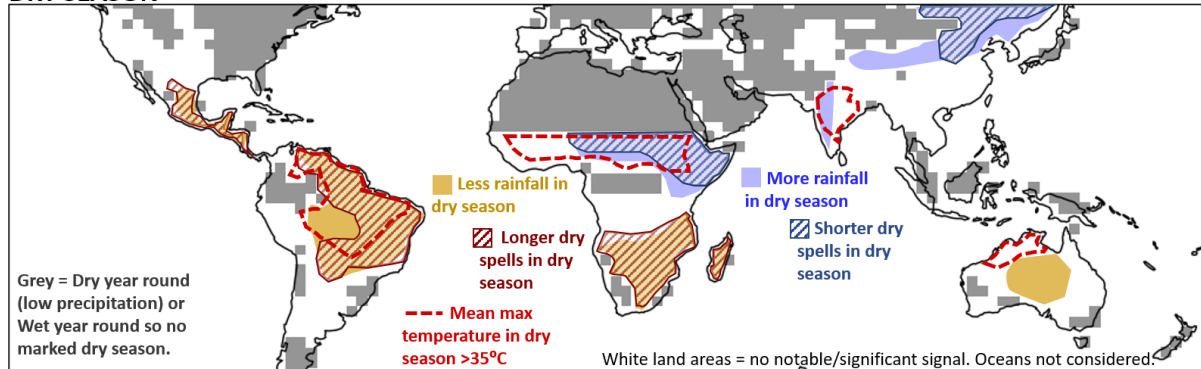


1055 FIG. 10. a) Region map showing the location of South Asia (SAS), East Asia (EAS), and South East Asia
 1056 (SEA). b-c) Boxplots showing the change in mean/max length of dry spells in the dry season. d-e) Boxplots
 1057 showing the change in mean/max length of wet spells in the wet season. The different colours indicate the CMIP
 1058 era (CMIP5 or CMIP6) and scenario (SSP 245, SSP 585, RCP 4.5, RCP 8.5). For all boxplots the change is
 1059 computed from the historical simulation for 1985-2014 to the select scenario for 2070-2099.

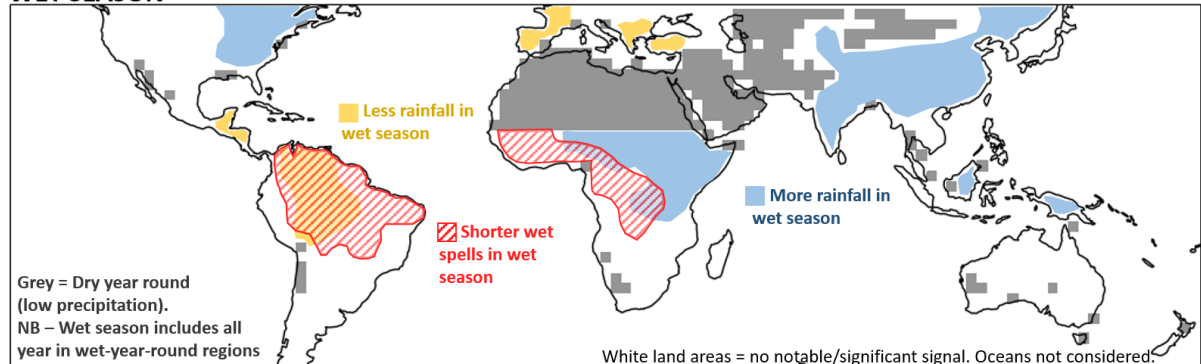


1060 FIG. 11. CMIP6 multi-model median change in a) mean wet season maximum daily temperature and b) mean
 1061 dry season maximum daily temperature for the SSP585 scenario over 2070-2099 compared with the historical
 1062 simulation over 1985-2014. The contours indicate where the CMIP6 multi-model median wet and dry season
 1063 mean daily maximum temperature is greater than 35°C for the historical simulation over 1985-2014 (dashed line)
 1064 and the SSP585 simulation over 2070-2099 (solid line). In all panels grey regions indicate where at least 50% of
 1065 the models do not give a value (dry year round or wet year round in the dry season plots).

DRY SEASON



WET SEASON



1066 FIG. 12. Schematic summarising the changes in wet/dry season rainfall and wet/dry
 1067 seasons found here; the top panel is for dry seasons and the bottom row is for wet seasons (including regions that
 1068 are wet year round).

1069 (Top) Longer dry spells and lower rainfall during the dry season are found over Central and South America and
 1070 Southern Africa. Shorter dry spells and more rainfall during the dry season are found over East Africa and parts
 1071 of Asia and the Sahel.

1072 (Bottom) More rainfall in the wet season is found over East Africa and Asia. Less rainfall in the wet season
 1073 is found over northern South America. Reductions in the length of wet spells in the wet season are found over
 1074 South America and West and Central Africa.