

Statistical projections of the mean changes in intra-seasonal rainfall characteristics over Zambia from the reference period 1981–2010 to the future 2031–2060

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This version replaces an earlier version of the manuscript: the analysis has been rebuilt, and the methods and results are new.

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Abstract

Zambia’s rain-fed agriculture depends less on how much rain falls in a season than on how that rain is distributed within it. This study projects changes in the longest dry spell (consecutive dry days, CDD) and the longest wet spell (consecutive wet days, CWD) over Zambia, together with the number of wet days, rainfall per wet day and seasonal total, for 2031–2060 relative to 1981–2010, using 25 CORDEX-Africa regional climate model simulations at 0.44° under RCP4.5 and RCP8.5. Both indices are computed in every grid cell from daily precipitation, separately for October–December (OND) and January–March (JFM), before any spatial averaging. The simulations are evaluated on the same indices against two daily observational products, CHIRPS and GPCC Full Data Daily, themselves checked against 18 rain gauges, and against reanalysis-driven runs of the same regional models. Because ensemble members share regional and driving models, significance is assessed over model families, and mapped tests control the false discovery rate. The observed OND dry spell is 17.5 days, which the simulations span from 12.7 to 34.7 days. The ensemble median projects the OND dry spell to lengthen by 2.23 days under RCP8.5 and 1.65 days under RCP4.5, with 95% of runs agreeing on the sign, and the number of OND wet days to fall by 2.7 and 2.0 days, while the seasonal total barely changes: early-season rain arrives on fewer days. The dry-spell lengthening survives false-discovery-rate control over 284 and 272 of 391 Zambian grid cells and is largest in Lusaka, Eastern, Muchinga and Central provinces. The OND wet spell shortens by 0.75 days (91% agreement), but the regional models disagree on it; rainfall per wet day rises in most runs but not robustly; and JFM changes are not robust. Treating the 22 runs as independent would give $p < 0.001$ for the headline result, against $p = 0.062$ when runs are first averaged within each regional model. An independent ensemble at 0.22° that shares no regional model with the primary one reproduces the observed dry spell more closely and projects a comparable change of 2.15 days. The results point to a more interrupted early rainy season and give no support for claims about the late season.

Introduction

Since the last century, the Earth’s surface temperature has risen by approximately 1°C , largely driven by increased anthropogenic greenhouse gas emissions from industrial, transportation, agricultural and deforestation activities [1, 2]. This warming has intensified the hydrological cycle, increasing the frequency, intensity and duration of extreme weather events such as droughts, floods and heat waves [3, 4]. In developing regions such as sub-Saharan Africa, adaptive capacity remains low, which compounds vulnerability to climatic extremes.

For rain-fed agriculture, the distribution of rainfall within a season is often more consequential than the seasonal total. A season that delivers normal rainfall in fewer, heavier events, separated by longer dry spells, can still fail: the critical period is the weeks after planting, when a prolonged dry spell destroys emerging crops [5, 6]. Indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI), in particular the maximum number of consecutive dry days (CDD) and consecutive wet days (CWD), are widely used to characterise exactly this aspect of a season [7, 8,

9]. Over 70% of Zambia’s population relies on rain-fed agriculture, so shifts in spell length present direct risks to food security and rural livelihoods [10, 11].

Regional Climate Models (RCMs), particularly those of the CORDEX-Africa framework, provide simulations at a resolution suitable for national impact studies [12, 13]. Many studies have evaluated the ability of RCMs to reproduce historical rainfall across Africa, generally finding that biases persist in individual models while ensembles capture observed variability more reliably [14, 15, 16, 17, 18, 19, 20]. Multi-model studies consistently project, under high-emission scenarios, an increase in CDD and a decrease in CWD across Southern Africa [21, 22, 23], consistent with a shortening rainy season through delayed onset, earlier cessation and longer intra-seasonal dry spells [24, 25, 26]. In Zambia, increased dry-spell frequency and reduced seasonal totals have already been reported, particularly in the southern and central provinces [27, 28]. Because these changes differ between regions of the country, the present study resolves them in every grid cell and province rather than as a single national figure.

Three gaps motivate the present study. First, national-scale analyses of Zambian rainfall extremes have often computed spell indices from a spatially averaged rainfall series. This is not a technical detail: averaging daily rainfall across a country before counting dry days removes local dry spells, because a dry day in one district is masked by rain in another, and it cannot produce the spatially resolved maps that adaptation planning requires. Second, spell indices are defined on daily data and must therefore be validated against daily observations; validation against monthly products cannot establish skill in spell length. Third, CORDEX is an ensemble of opportunity rather than a designed sample: its members share regional models and driving global models, so statistics that treat members as independent overstate confidence [29].

We address these gaps directly. Daily precipitation from 25 CORDEX-Africa simulations is used to compute CDD, CWD and three related indices *per grid cell* for the OND and JFM seasons; models are evaluated on those same indices against two independent daily observational products and against reanalysis-driven runs; and significance is assessed in a way that accounts for model dependence and for multiple testing across grid cells. The study reports projected changes for 2031–2060 relative to a 1981–2010 baseline under both RCP4.5 and RCP8.5, identifies where in Zambia the changes are largest, and repeats the entire analysis with an independent higher-resolution ensemble as a test of robustness.

A note on model generation is warranted. Downscaled projections for Africa in the CMIP6 generation were not available for this analysis: a search of the ESGF index nodes that serve CORDEX (CEDA, DKRZ and NSC) on 23 September 2026 returned no CORDEX-CMIP6 precipitation data for any African domain, while the same query for CORDEX-Africa returned 107 datasets. Independently, CMIP6 global models continue to show wide inter-model spread and a widespread wet bias over Zambia, linked to an overly intensified simulated Inter-Tropical Convergence Zone [30], and bias-correction assessments over Southern Africa report persistent difficulty in representing CDD in particular [31]. Dynamically downscaled, multi-RCM CORDEX ensembles therefore remain the appropriate basis for sub-national projections of rainfall extremes over Zambia, and the secondary ensemble used here (Section Secondary ensemble at higher resolution) tests the sensitivity of the conclusions to the generation and

resolution of the downscaling.

Materials and methods

Study area and analysis grid

Zambia lies between approximately 8° – 18° S and 22° – 34° E in south-central Africa, on a plateau of 1,000–1,600 m with lower-lying valleys along the Zambezi and Luangwa rivers [32, 33]. Its climate is tropical with a single rainy season from November to April, driven by the seasonal migration of the Inter-Tropical Convergence Zone [32, 6]. Rainfall decreases from north to south, from above 1,200 mm annually in Northern and Luapula provinces to below 700 mm in the Southern valley [34, 35].

Agricultural planning in Zambia uses three agro-ecological regions, defined by rainfall (Fig 1) [35]. Region I, in the south and along the Zambezi and Luangwa valleys, receives 800 mm a year or less, carries a medium to high risk of drought and is used mainly for small grains and livestock. Region II receives 800 to 1,000 mm, has a medium to low risk of drought, and is subdivided by agricultural potential rather than by rainfall: Region IIa, on the central and eastern plateau, is the country’s most productive area for both food and cash crops, while Region IIb, in the west, is suited mainly to cassava, rice and cattle. Region III, in the north, receives more than 1,000 mm, carries a very low risk of drought, and is predominantly a cassava-growing region [35]. The analysis itself is carried out by grid cell and by province, the administrative unit in which agricultural support is delivered; the agro-ecological regions are used to interpret where the projected changes fall. Provinces are those of the present administrative division, which has ten provinces since Muchinga was created in 2011 from parts of Northern and Eastern provinces; sources published before 2011, including some cited here, describe nine.

The analysis is performed on the native CORDEX-Africa rotated grid at 0.44° (≈ 49 km), clipped to 20.24° – 34.76° E and 19.80° – 6.16° S: 34×32 cells with a margin of 1 – 2° beyond the national border. All indices are computed on this rectangle. For mapping and for national or provincial averages, each cell is weighted by the fraction of its area inside Zambia, obtained by intersecting each cell with the national boundary, multiplied by the cosine of latitude. Summed, these fractions reproduce Zambia’s area as 755,695 km² against an actual 752,618 km² (+0.4%). Province boundaries follow the 2022 district boundaries of Zambia’s National Spatial Data Infrastructure, dissolved to provinces. Of the 1,088 cells, 391 contain Zambian land and 262 lie wholly inside. Cells outside Zambia are not shown on any map.

Regional climate model data

Daily precipitation from the CORDEX-Africa ensemble (domain AFR-44, 0.44°) was obtained from the Earth System Grid Federation. The ensemble comprises six regional climate models: CCLM4-8-17, the COSMO model in Climate Mode [36]; HIRHAM5, the HIRHAM regional climate model [37]; RACMO22T, the Regional Atmospheric Climate Model [38]; RCA4, the Rossby Centre regional atmospheric model [39]; REMO2009, the Regional Model [40]; and CRCM5, the fifth-generation Canadian Regional Climate Model [41]. They are driven by twelve global climate models, giving 25

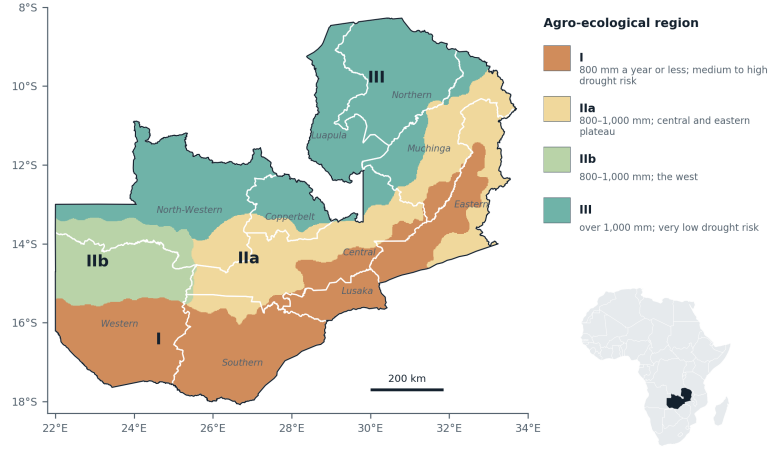


Fig 1. Agro-ecological regions of Zambia. Region I (800 mm of rain a year or less; the south and the Zambezi and Luangwa valleys), Region IIa (800–1,000 mm; the central and eastern plateau, the most productive area for food and cash crops), Region IIb (800–1,000 mm; the west, suited mainly to cassava, rice and cattle) and Region III (more than 1,000 mm; the north). White lines are the province boundaries used throughout this study; the inset shows Zambia’s location in Africa. Adapted from Phiri et al. [34] under a CC BY 4.0 licence: the regions were digitised from their map and redrawn on the provincial boundaries of this study.

GCM–RCM runs with historical simulations, of which 22 have a paired RCP8.5 run and 21 a paired RCP4.5 run. Each GCM–RCM combination provides exactly one ensemble member (**r1i1p1**, or the single member published for that combination), so no model is represented more than once through multiple realisations. The full inventory is given in Table 1 and, with the secondary ensemble and the reanalysis-driven runs, in S1 Table. One run used in an earlier version of this analysis, NorESM1-M driven HIRHAM5, has since been retracted by its producer and is excluded.

Observations

CHIRPS v2.0 daily precipitation at 0.25° is the primary reference [42]. It blends satellite infrared estimates with station observations and has been validated against independent gauges over eastern Africa, where it compared favourably with other satellite-based products [43]. It is conservatively remapped to the 0.44° model grid before any index is computed, because spell indices depend on grid scale: a coarser cell averages away dry days, so models and observations must be compared on one grid.

GPCC Full Data Daily v2018 at 0.5° (1982–2010), a gauge-only product, is used as an independent second reference [44, 45], remapped the same way. Its gauge support over Zambia is uneven and sparse, and is reported explicitly: in 1995 the product carries on average 0.02 gauges per 0.5° cell per day over the country, equivalent to roughly 17 gauges on a typical day. Using a satellite-gauge product and a gauge-only product side by side, rather than either alone, makes the observational uncertainty measurable. Every evaluation metric is computed against both products, and the two

Table 1. The CORDEX-Africa ensemble used in this study.
Domain AFR-44 at 0.44°, one member per GCM–RCM combination;
“Member” is the realisation of the driving global model. Codes are those
of the thesis on which the study is based and are used only in the
supporting tables. M23 (NorESM1-M driven HIRHAM5) was used in an
earlier version of this analysis and has since been retracted by its
producer; it is excluded. Totals: 25 historical, 21 RCP4.5, 22 RCP8.5.

Code	Driving global model	Member	Regional model	Institution	Hist.	RCP4.5	RCP8.5
M1	CCCma-CanESM2	r1i1p1	CRCM5	UQAM	✓	✓	
M2	CCCma-CanESM2	r1i1p1	RCA4	SMHI	✓	✓	✓
M3	CNRM-CM5	r1i1p1	CCLM4-8-17	CLMcom	✓	✓	✓
M4	CNRM-CM5	r1i1p1	RCA4	SMHI	✓	✓	✓
M5	CSIRO-Mk3-6-0	r1i1p1	RCA4	SMHI	✓	✓	✓
M6	EC-EARTH	r12i1p1	CCLM4-8-17	CLMcom	✓	✓	✓
M7	EC-EARTH	r3i1p1	HIRHAM5	DMI	✓	✓	✓
M8	EC-EARTH	r12i1p1	REMO2009	MPI-CSC	✓	✓	✓
M9	EC-EARTH	r1i1p1	RACMO22T	KNMI	✓	✓	✓
M10	EC-EARTH	r12i1p1	RCA4	SMHI	✓	✓	✓
M11	IPSL-CM5A-LR	r1i1p1	REMO2009	GERICS	✓		✓
M12	IPSL-CM5A-MR	r1i1p1	RCA4	SMHI	✓	✓	✓
M13	MIROC5	r1i1p1	REMO2009	GERICS	✓		✓
M14	MIROC5	r1i1p1	RCA4	SMHI	✓	✓	✓
M15	HadGEM2-ES	r1i1p1	CCLM4-8-17	CLMcom	✓	✓	✓
M16	HadGEM2-ES	r1i1p1	REMO2009	GERICS	✓		✓
M17	HadGEM2-ES	r1i1p1	RACMO22T	KNMI	✓	✓	✓
M18	HadGEM2-ES	r1i1p1	RCA4	SMHI	✓	✓	✓
M19	MPI-ESM-LR	r1i1p1	CCLM4-8-17	CLMcom	✓	✓	✓
M20	MPI-ESM-LR	r1i1p1	CRCM5	UQAM	✓	✓	
M21	MPI-ESM-LR	r1i1p1	REMO2009	MPI-CSC	✓	✓	✓
M22	MPI-ESM-LR	r1i1p1	RCA4	SMHI	✓	✓	✓
M24	NorESM1-M	r1i1p1	RCA4	SMHI	✓	✓	✓
M25	GFDL-ESM2G	r1i1p1	REMO2009	GERICS	✓		
M26	GFDL-ESM2M	r1i1p1	RCA4	SMHI	✓	✓	✓

are also compared with each other over their 28 common season-years. Over Zambia in OND the mean longest dry spell is 17.6 days in CHIRPS and 18.9 days in GPCC, and the mean longest wet spell 14.3 days against 9.5 days. Because the wet-spell disagreement of 4.8 days is larger than any projected change in that index, and larger than the bias of 20 of the 25 GCM-driven runs, no conclusion in this paper rests on the magnitude of the wet spell. A model bias smaller than the gap between the two observational products is not reported as an error of the model.

Both products were checked against rain gauges. Daily records for 18 Zambian stations, in nine of the ten provinces (none in Muchinga), are available from the Global Historical Climatology Network-Daily database [46] for 1981–1990; later years are too incomplete to use. Every station lacks the same days each year (the 31st of each 31-day month and 14–15 February), so seasons with up to four missing days were accepted (333 station-seasons), and the missing days were removed from the gridded series as well, so that a gap breaks a spell identically in both. Each product was compared at the

station’s own cell, at its native resolution and on the model grid (S2 Fig). For the OND dry spell both products reproduce the gauges closely: the spatial correlation of the station means is 0.92 to 0.93, and the gauges lie between the two products, CHIRPS being 1.0 day shorter and GPCC 1.8 days longer on the model grid. For the wet spell they diverge. GPCC matches the gauges (median bias -0.7 days in both seasons), whereas CHIRPS is 6.1 days longer in OND and 7.2 days longer in JFM, with 6 and 20 more wet days per season. Because GPCC is also an area average, the excess in CHIRPS is not a point-versus-area effect alone. The seasonal total is less decisive: in OND both products fall short of the gauges, CHIRPS by 95 mm and GPCC by 57 mm, while in JFM both are within about 40 mm of them. The gauges therefore support the difference between the two products as the observational uncertainty of the dry spell, and indicate that CHIRPS overstates wet spells over Zambia. Both products assimilate gauge data, possibly from these stations: in 1982–1990 the GPCC cell containing a station held at least one gauge on a median of 29% of days. This is therefore a check on how well the products represent spells at gauges, not a fully independent validation.

Periods and scenarios

The baseline and the evaluation period are identical: 1981–2010, a 30-year WMO normal. The current normal, 1991–2020, is not used because CORDEX historical experiments end in 2005, so half of that period would have to come from the scenario runs. The future period is 2031–2060. The baseline uses the historical simulations to 2005 and the first five years of the scenario runs (2006–2010); the two scenarios have almost identical forcing over those five years, so a single baseline is used for both, which keeps the comparisons consistent.

Two Representative Concentration Pathways are used [47]. RCP8.5 is a high-emission pathway in which greenhouse-gas emissions continue to rise throughout the century, reaching a radiative forcing of about 8.5 W m^{-2} by 2100. RCP4.5 is an intermediate pathway in which emissions peak around the middle of the century and forcing stabilises near 4.5 W m^{-2} after 2100. Neither is a forecast. Every projection in this paper is conditional on its scenario, and RCP8.5 is treated as a high-emission bound rather than as the most likely future.

Preprocessing

Every step is scripted. The scripts, the derived index files and the results tables are deposited at Zenodo [48].

1. **Units.** Model precipitation is a flux in $\text{kg m}^{-2} \text{ s}^{-1}$ and is multiplied by 86,400 once, at series assembly, to give mm day^{-1} .
2. **Spatial subset.** Files are clipped to the analysis rectangle by grid index.
3. **Calendars and leap days.** The ensemble mixes 360-day, 365-day and Gregorian calendars. No calendar conversion or interpolation is applied, and leap days are kept where a calendar has them. Every index is a count of days or a rate within a single season, so no day is ever paired across calendars, and the season length of each run is recorded alongside its indices.

4. **Integrity and missing values.** Each downloaded file was verified against the SHA256 checksum published in the ESGF index; server-side subsets were verified by reproducing checksum-verified full downloads exactly. Clipped files were checked for the expected grid, complete dates, and absence of missing values.
5. **Regridding.** Only the observations are regridded, conservatively, to the model grid [49], with one stated exception: RegCM4-7 in the secondary ensemble, which is distributed on a different map projection and is conservatively remapped to the grid of the other models in that ensemble (Section Secondary ensemble at higher resolution). No model field in the primary ensemble is interpolated.

Indices

For each grid cell, each season and each year, five indices are computed from daily precipitation P_d (mm), $d = 1, \dots, N$, where N is the number of days in the season in that run’s calendar, and $1 \leq a \leq b \leq N$ index the first and last days of a spell. A day is wet if $P_d \geq 1$ mm and dry otherwise. This is the ETCCDI threshold [7], and also the one the Zambia Meteorological Department uses operationally, defining a prolonged dry spell as more than 10 days with less than 1 mm of rain [50]. The indices are

$$\text{CDD} = \max \{ b - a + 1 : P_d < 1 \ \forall d \in [a, b] \}, \quad (1)$$

$$\text{CWD} = \max \{ b - a + 1 : P_d \geq 1 \ \forall d \in [a, b] \}, \quad (2)$$

$$\text{PRCPTOT} = \sum_{d=1}^N P_d, \quad \text{RR1} = \#\{ d : P_d \geq 1 \}, \quad (3)$$

$$\text{SDII} = \text{PRCPTOT}/\text{RR1}, \quad (4)$$

that is, the longest dry spell, the longest wet spell, the seasonal total, the number of wet days and the mean rainfall per wet day. Seasons are OND (1 October to 31 December of year Y) and JFM (1 January to 31 March of year $Y + 1$), labelled by the start year Y . OND covers the onset of the rains and the planting period; JFM covers the core of the rainy season. A season-year is used only when both its OND and the following JFM are present, which gives 29 season-years in each 30-year period (1981/82 to 2009/10 and 2031/32 to 2059/60).

Two properties follow from computing the indices this way. First, each index is computed independently in every grid cell, from daily data, before any spatial averaging. Second, a spell is measured only within one season window, so a seasonal spell can never exceed the length of that season ($\text{CDD}, \text{CWD} \leq N$).

Evaluation design

Runs are evaluated on the same indices the study projects, not on monthly or seasonal totals, and against both observational products rather than one.

A global-model-driven simulation is not synchronised with observed weather: its 1995 is not the real 1995. Year-by-year correlation against observations is therefore not a meaningful test for these runs and is not used. The same applies to efficiency scores such as the Nash–Sutcliffe and Kling–Gupta efficiencies, and to the correlation and centred root-mean-square difference summarised in a Taylor diagram: all compare two series time

step by time step, and for unsynchronised simulations they measure chance agreement rather than skill. The GCM-driven runs are instead assessed on the 30-year mean of each index (bias, Zambia-weighted), on the spatial pattern of that mean (pattern correlation), and on the ratio of interannual standard deviation to observed. To test the regional models themselves, the ensemble is complemented by reanalysis-driven (ERA-Interim) runs of the same regional models. These *are* synchronised with observed weather, so for them a year-by-year comparison is valid and is reported (S2 Table).

Projected change and significance

The change for each run r and index I is its own future mean minus its own baseline mean, $\Delta I_r = \bar{I}_{r, 2031-2060} - \bar{I}_{r, 1981-2010}$, so only paired runs contribute. The ensemble statistic is the median of ΔI_r over all paired members, reported with its interquartile range; agreement is reported separately as the percentage of members sharing the sign of the median.

CORDEX is an ensemble of opportunity and its members are not independent [29]: ten of the 22 RCP8.5 runs share RCA4, and EC-EARTH drives five runs through five different regional models. Significance is therefore assessed with a two-sided sign test applied three ways: over all members, which is the optimistic bound; over regional-model families, after averaging ΔI_r within each regional model; and over driving-model families, after averaging within each global model. For n values of which k are positive (zeros are discarded), the null hypothesis is that positive and negative changes are equally likely, and

$$p = \min \left\{ 1, 2 \sum_{i=0}^{\min(k, n-k)} \binom{n}{i} 2^{-n} \right\}. \quad (5)$$

The sign test makes no assumption about the distribution of the changes. The family-based tests are the ones on which conclusions rest, and a change is described as robust only when it holds across regional models as well as across driving models: the regional-model families must agree unanimously on its sign (with five or six families the test can go no lower than 0.063 or 0.031) and the driving-model test must give $p < 0.05$. Because each regional model counts once, a model represented by a single run carries the same weight as one represented by ten; all three tests are reported so that readers can see the effect of the choice.

A map of Zambia at this resolution is 391 tests, one per cell. At $p < 0.05$, twenty cells would be expected to appear significant even if nothing changed anywhere [51]. Each cell is therefore tested with the same family-aware sign test used for the national figures, and the resulting p -values are corrected across the 391 Zambian cells by the Benjamini–Hochberg procedure at $q = 0.10$ [52], which is valid under the positive spatial dependence these fields exhibit [53]. Maps report the corrected result, and the uncorrected p -value of every cell is archived alongside it. One consequence must be stated plainly: with five regional-model families in the RCP8.5 ensemble, a sign test cannot return a p below $2/2^5 = 0.063$ however unanimous the families are, so the per-cell test is coarse by construction and failure to reject is not evidence of no change. It also means that at $q = 0.05$ no cell could survive the correction. The level $q = 0.10$ is the one recommended for spatially correlated fields, where it corresponds to a global test at the 0.05 level [51], and the maps should be read with that choice in mind.

Secondary ensemble at higher resolution

To test whether the results depend on the generation and resolution of the downscaling, the whole analysis is repeated with CORDEX-CORE simulations at 0.22° (≈ 25 km) [54], obtained from the Copernicus Climate Change Service, using the regional models CCLM5-0-15 [36], REMO2015 [40], CanRCM4 [55] and RegCM4-7 [56] driven by CanESM2, HadGEM2-ES, MPI-ESM-LR, MPI-ESM-MR and NorESM1-M: ten GCM-driven runs under RCP8.5 in four regional-model families, one run under RCP4.5, and four reanalysis-driven runs. This ensemble shares no regional model with the primary one, so it is an independent test of the result rather than a refinement of it.

RegCM4-7 is distributed on a Mercator projection at 25 km rather than on the rotated-pole 0.22° grid shared by the other three regional models, and it is the only model field in this study that is interpolated. Each daily field is remapped conservatively to the 0.22° grid [49], with the source cell edges computed exactly from the projection. The remap conserves the area-integrated rainfall of every file to better than one part in 10^6 . Conserving the total does not conserve spell statistics, so the effect on the indices was measured directly, by computing them on both grids over the same area for 1981–2005. The remap shortens the mean longest OND dry spell by 0.08 to 0.12 days and lengthens the longest wet spell by 1.0 to 1.4 days in OND and 2.1 to 2.6 days in JFM, as expected when neighbouring cells are averaged. Because this shift is almost the same in the baseline and the future, the projected RCP8.5 change is nearly unaffected: by at most 0.03 days for the OND dry spell and at most 0.18 days for either wet spell. All 0.22° statistics are nevertheless reported both with and without RegCM4-7, so that its contribution can be seen.

The two ensembles are reported side by side and are never pooled. They are analysed on their own grids, each with its own Zambia mask and its own conservatively remapped observations, because grid scale alone changes spell statistics: remapping CHIRPS to the 0.22° grid rather than the 0.44° grid leaves the seasonal total unchanged to four significant figures but moves the mean longest wet spell by 1.1 days. Pooling ensembles of different resolution would mix that shift into the model spread.

Results

How well the simulations reproduce observed spells

Over Zambia in OND, the observed longest dry spell is 17.5 days and the observed longest wet spell 14.0 days (CHIRPS, 1981–2010, area-weighted). Across the 25 GCM-driven runs the simulated OND dry spell ranges from 12.7 to 34.7 days, a bias of -4.8 to $+17.3$ days (Fig 2). The ensemble does not fail uniformly: five runs lie within 1.3 days of CHIRPS, the size of the gap between the two observational products, while the poorest overestimate the dry spell by more than two weeks. Some regional models err in a consistent direction whatever drives them: five of the six REMO2009 runs underestimate the OND dry spell and all four CCLM4-8-17 runs overestimate it, whereas the RCA4 runs span almost the whole range, from -4.8 to $+14.9$ days, depending on the driving model. Metrics for every run, index, season and reference are given in S2 Table.

Spatial pattern correlation conceals this. Pattern correlations range

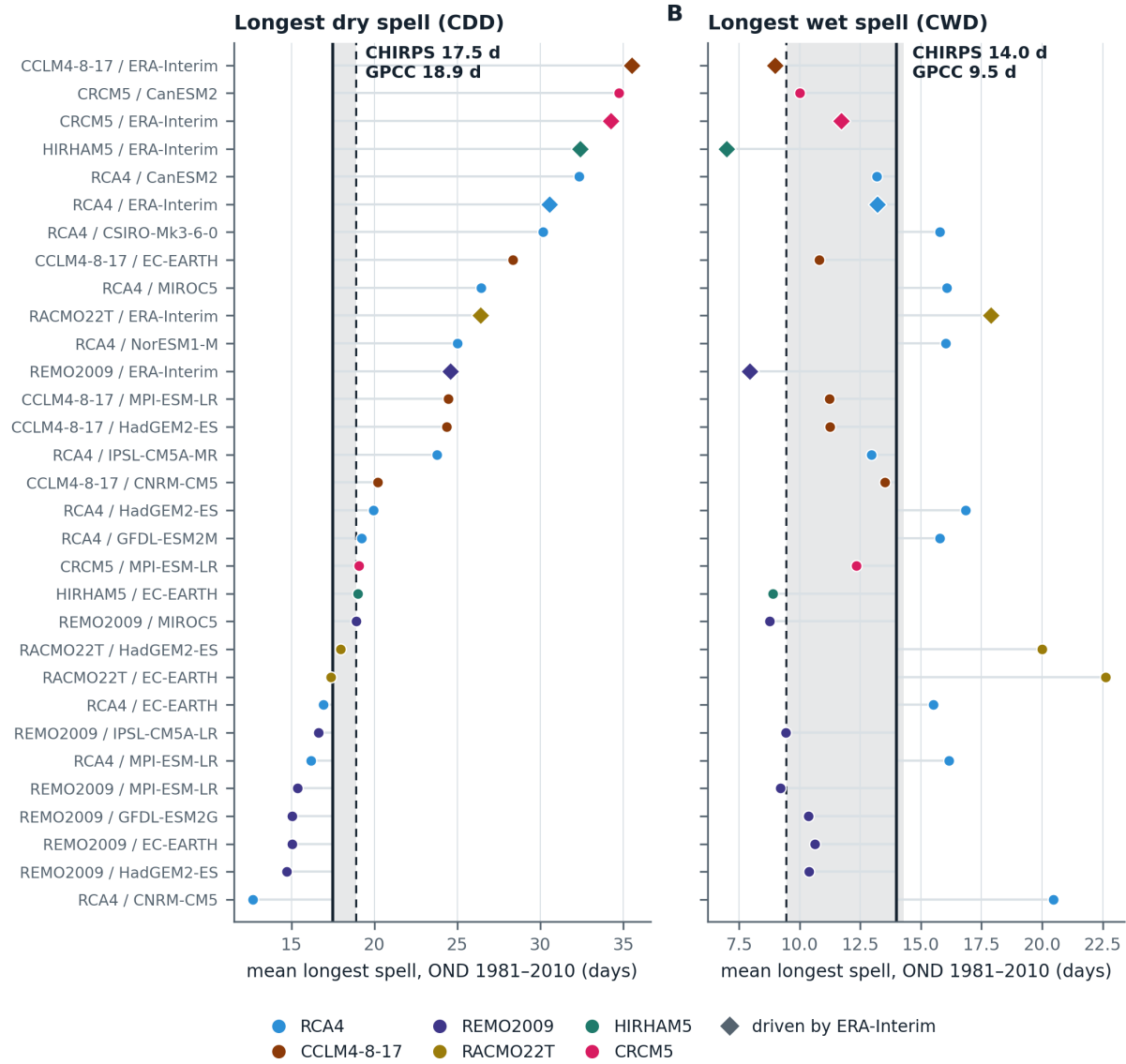


Fig 2. Every run against the observations, October–December (OND), 1981–2010. (A) Mean longest dry spell (CDD) and (B) mean longest wet spell (CWD) over Zambia, in days, for each run, labelled by regional model and driving model and coloured by regional model. Circles are driven by a global climate model; diamonds are driven by ERA-Interim reanalysis. The solid line is CHIRPS, the dashed line GPCC; the shaded band between them spans the two observational products, so a run inside it differs from CHIRPS by less than CHIRPS differs from GPCC.

from 0.44 to 0.91, and the highest value in the ensemble, $r = 0.91$, belongs to a run that overestimates the dry spell by seven days. A high spatial correlation indicates that a model places wetter and drier regions correctly; it is not evidence of skill in spell length, and should not be reported as

though it were.

For the other three indices the observational uncertainty is larger still. In OND, CHIRPS and GPCC differ by 6.6 wet days (43.3 against 37.4), by 74 mm in the seasonal total (342 against 421 mm) and by 3.5 mm in the mean rainfall per wet day (7.8 against 11.3 mm). The simulations lie mostly between the two products: their median bias is -1.1 wet days against CHIRPS and $+4.9$ against GPCC, $+70$ mm and -12 mm in the total, and $+2.0$ and -1.4 mm in rainfall per wet day. Pattern correlations are lower than for the dry spell, reaching 0.94 for wet days but no more than 0.87 for the total and 0.59 for rainfall per wet day (S2 Table).

The reanalysis-driven runs are more informative than their number suggests. Driven by observed weather, RCA4 overestimates the OND dry spell by 13.1 days and produces too few wet days (35.4 against 43.3 observed). Driven by MPI-ESM-LR, the same regional model shows a bias of only -1.3 days, because that global model is too wet (49.9 wet days). Two compensating errors produce an apparently unbiased simulation. Without the reanalysis-driven runs this cancellation is invisible, and a model-selection procedure based on bias alone would have preferred the compensating pair.

Projected changes in spells, wet days and rainfall

The ensemble median projects the OND dry spell to lengthen by 2.23 days under RCP8.5 and 1.65 days under RCP4.5 by 2031–2060, with 95% of runs agreeing on the sign in both scenarios (Table 2, Fig 3). The scenarios order as expected, RCP8.5 exceeding RCP4.5, which is a useful internal consistency check. Every regional-model family agrees on the lengthening, and so do the driving-model families ($p = 0.001$ and 0.021). Per-run changes for every index are given in S3 Table.

The OND wet spell shortens, by 0.75 days under RCP8.5 and 0.66 days under RCP4.5, so both spells point the same way: in the early season, runs of rain become shorter and the breaks between them longer. The direction of the wet-spell change is well supported, with 91% of runs agreeing under RCP8.5, but its significance is not. The two runs that lengthen it are both RACMO22T ($+1.4$ and $+2.4$ days), while every other regional model shortens it. Grouped by driving model the change is significant ($p = 0.012$); grouped by regional model, four of five families agree and $p = 0.375$. The wet-spell change is therefore consistent across global drivers but not across regional models, and it does not meet the criterion for a robust change set out in the Methods. Its magnitude is limited by the observations as well: CHIRPS and GPCC differ by 4.8 days in the observed OND wet spell, several times the projected change. The wet-spell shortening is reported as a consistent direction of change, not as an established one.

The other three indices show how the early season changes (Table 2). The number of OND wet days falls by 2.67 days under RCP8.5, with every run agreeing, and by 2.03 days under RCP4.5 (90% agreement). Every regional-model family agrees on the loss in both scenarios, and so do the driving-model families ($p = 0.001$ and 0.021), so it meets the criterion for a robust change. The OND seasonal total, by contrast, barely changes: -3.2 mm under RCP8.5 and -5.8 mm under RCP4.5, less than 2% of the observed total, with only 64% and 67% of runs agreeing on the sign. Early-season rain therefore arrives on fewer days rather than in smaller amounts, which is consistent with the longer dry spell: with fewer wet days in the same season, the gaps between them lengthen. The mean rainfall per

Table 2. Projected change in the rainfall characteristics of the season over Zambia, 2031–2060 relative to 1981–2010. Values are area-weighted ensemble medians, with the interquartile range (IQR) across runs. CDD, longest dry spell; CWD, longest wet spell; RR1, number of wet days; SDII, mean rainfall per wet day; PRCPTOT, seasonal total. “Agree” is the percentage of runs sharing the sign of the median. p values are two-sided sign tests over all members (all), over regional-model (RCM) families and over driving-model (GCM) families. OND, October–December; JFM, January–March.

Scen.	Season	Index	Unit	n	Median	IQR	Agree	p (all)	p (RCM)	p (GCM)
RCP8.5	OND	CDD	days	22	+2.23	+1.46 to +3.17	95%	< 0.001	0.062	0.001
RCP8.5	OND	CWD	days	22	−0.75	−1.18 to −0.24	91%	< 0.001	0.375	0.012
RCP8.5	OND	RR1	days	22	−2.67	−3.31 to −2.03	100%	< 0.001	0.062	0.001
RCP8.5	OND	SDII	mm/day	22	+0.60	+0.35 to +0.72	86%	0.001	0.375	0.001
RCP8.5	OND	PRCPTOT	mm	22	−3	−18 to +11	64%	0.286	0.375	1.000
RCP8.5	JFM	CDD	days	22	+0.51	−0.33 to +1.16	68%	0.134	0.375	0.065
RCP8.5	JFM	CWD	days	22	−0.85	−1.63 to −0.10	73%	0.052	1.000	0.012
RCP8.5	JFM	RR1	days	22	−1.63	−2.75 to +0.49	68%	0.134	1.000	0.227
RCP8.5	JFM	SDII	mm/day	22	+0.62	+0.28 to +0.82	86%	0.001	0.375	0.001
RCP8.5	JFM	PRCPTOT	mm	22	+6	−3 to +32	64%	0.286	0.375	0.065
RCP4.5	OND	CDD	days	21	+1.65	+0.89 to +2.73	95%	< 0.001	0.031	0.021
RCP4.5	OND	CWD	days	21	−0.66	−0.91 to −0.18	81%	0.007	0.219	0.021
RCP4.5	OND	RR1	days	21	−2.03	−2.27 to −1.08	90%	< 0.001	0.031	0.021
RCP4.5	OND	SDII	mm/day	21	+0.31	+0.17 to +0.50	90%	< 0.001	0.219	0.002
RCP4.5	OND	PRCPTOT	mm	21	−6	−10 to +3	67%	0.189	0.688	0.344
RCP4.5	JFM	CDD	days	21	+0.49	−0.24 to +0.96	67%	0.189	0.688	0.754
RCP4.5	JFM	CWD	days	21	−0.96	−1.31 to +0.07	71%	0.078	0.688	0.109
RCP4.5	JFM	RR1	days	21	−1.01	−2.32 to +0.25	67%	0.189	0.031	0.109
RCP4.5	JFM	SDII	mm/day	21	+0.44	+0.16 to +0.47	81%	0.007	0.219	0.002
RCP4.5	JFM	PRCPTOT	mm	21	+9	−8 to +22	67%	0.189	1.000	0.344

wet day rises accordingly in most runs, by 0.60 mm under RCP8.5 (86% agreement) and 0.31 mm under RCP4.5 (90%), but the regional models disagree on it ($p = 0.375$ and 0.219), so the increase in intensity is not claimed as robust. In JFM none of the three indices changes robustly: wet days fall by 1.63 and 1.01 days with 68% and 67% agreement, and neither the total nor the rainfall per wet day passes the family tests.

Changes in the JFM season are not robust. The OND-to-JFM contrast is stark: JFM dry spells change by 0.51 days (RCP8.5) and 0.49 days (RCP4.5) with only 68% and 67% of runs agreeing on the sign, and no family test falls below 0.05. The JFM wet spell shortens by 0.85 and 0.96 days with 73% and 71% agreement. Under RCP8.5, ten of the eleven driving-model families agree on that shortening ($p = 0.012$), but the regional-model families divide ($p = 1.000$): RCA4, REMO2009 and HIRHAM5 shorten the JFM wet spell while CCLM4-8-17 and RACMO22T lengthen it. The paper therefore reports no late-season change rather than a small number with a wide spread behind it.

The distinction between member-level and family-level testing is material rather than technical. For the headline result, treating the 22 runs as independent gives $p < 0.001$; averaging runs within each regional model first gives $p = 0.062$ (Fig 4). Most of the apparent significance came from

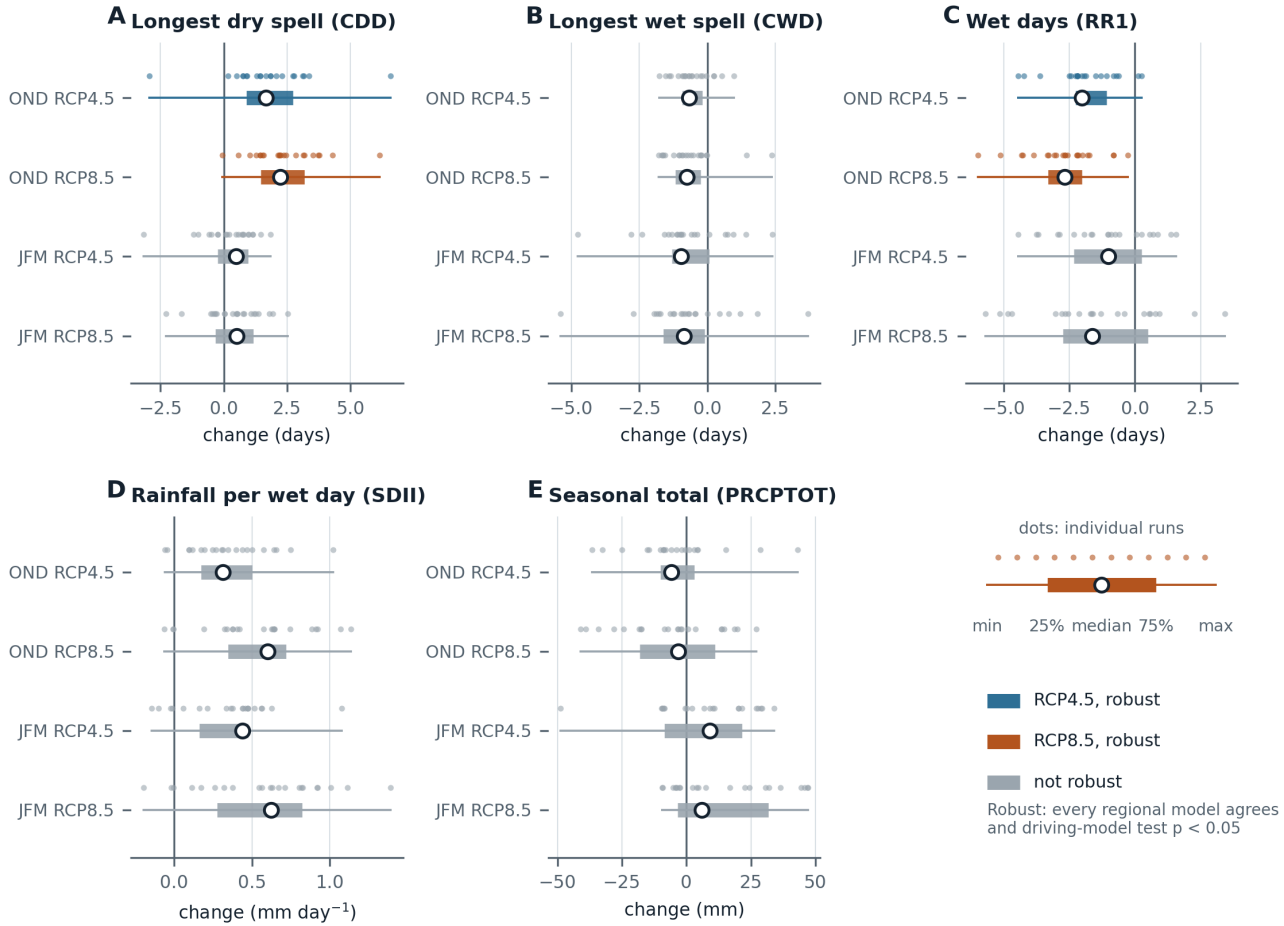


Fig 3. Spread of the projected change across the ensemble, 2031–2060 minus 1981–2010. (A) Longest dry spell, (B) longest wet spell and (C) number of wet days, in days; (D) mean rainfall per wet day, in mm day^{-1} ; (E) seasonal total, in mm; for October–December (OND) and January–March (JFM) under RCP4.5 and RCP8.5. For each case the dots are the individual runs, the thick bar spans the interquartile range, the thin line the full range, and the circle marks the ensemble median. A change drawn in colour meets the robustness criterion of the Methods: every regional-model family agrees on its sign and the driving-model test gives $p < 0.05$. Changes drawn in grey do not.

counting RCA4 ten times. The wet-spell shortening illustrates the same point more sharply: 91% of runs agree on the sign under RCP8.5, yet the by-regional-model test gives $p = 0.375$, because the disagreement is concentrated in one regional model. Agreement and significance are different quantities, and both are reported here.

The result does not depend on runs that reproduce the observed dry spell poorly. Retaining only the 14 RCP8.5 runs whose OND dry-spell bias lies within 5 days of CHIRPS, which still include all five regional models, gives a median change of +2.23 days with every run agreeing on the sign; thresholds of 3 and 10 days give +2.24 and +2.21 days. The same

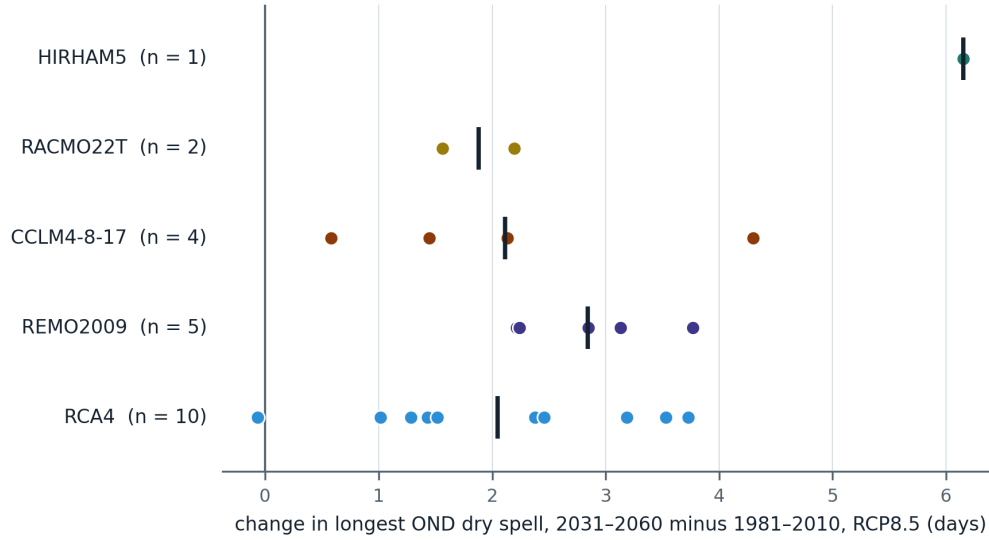


Fig 4. Why the runs are not independent samples. Change in the longest October–December dry spell, 2031–2060 minus 1981–2010 under RCP8.5, for each of the 22 runs (dots), grouped by regional model; n is the number of runs of each regional model. Ten of the 22 runs share RCA4. Vertical bars are family means: the regional-model test on which the conclusions rest uses these five values, not the 22 dots.

restriction under RCP4.5 (12 runs, all six regional models) gives +1.44 days, again with every run agreeing, although with fewer driving models the driving-model test rises to $p = 0.062$. Weighting runs by their skill would therefore not change the conclusion, and all runs are retained.

Where the change occurs

After controlling the false discovery rate across the 391 Zambian cells, the OND dry-spell lengthening survives over 284 cells under RCP8.5 and 272 under RCP4.5 (Fig 5). No cell survives for the OND wet spell, or for either spell index in JFM. The loss of OND wet days survives over 273 cells under RCP8.5 and 151 under RCP4.5 (S3 Fig), and nothing survives for rainfall per wet day or the seasonal total. JFM wet days survive over 133 cells under RCP4.5 but over none under RCP8.5, and the national driving-model test for that change gives only $p = 0.109$, so it is not treated as a result. The early-season changes, longer dry spells and fewer wet days, are therefore the only mapped results the data support, and the dry-spell lengthening covers roughly seven tenths of the country. The wet-spell maps are shown with the same care because their empty result is informative: the OND wet spell shortens almost everywhere but nowhere by enough, across regional models, to survive correction. The JFM wet-spell maps show the strongest colours in the figure, a shortening of up to three days across the north, and none of it survives. That is exactly the pattern that uncorrected, stippled maps invite readers to over-interpret. The ensemble spread and sign agreement behind each cell are mapped in S1 Fig.

The largest increases fall in a central and eastern band: Lusaka (+2.93 days under RCP8.5), Eastern (+2.90), Muchinga (+2.89) and Central

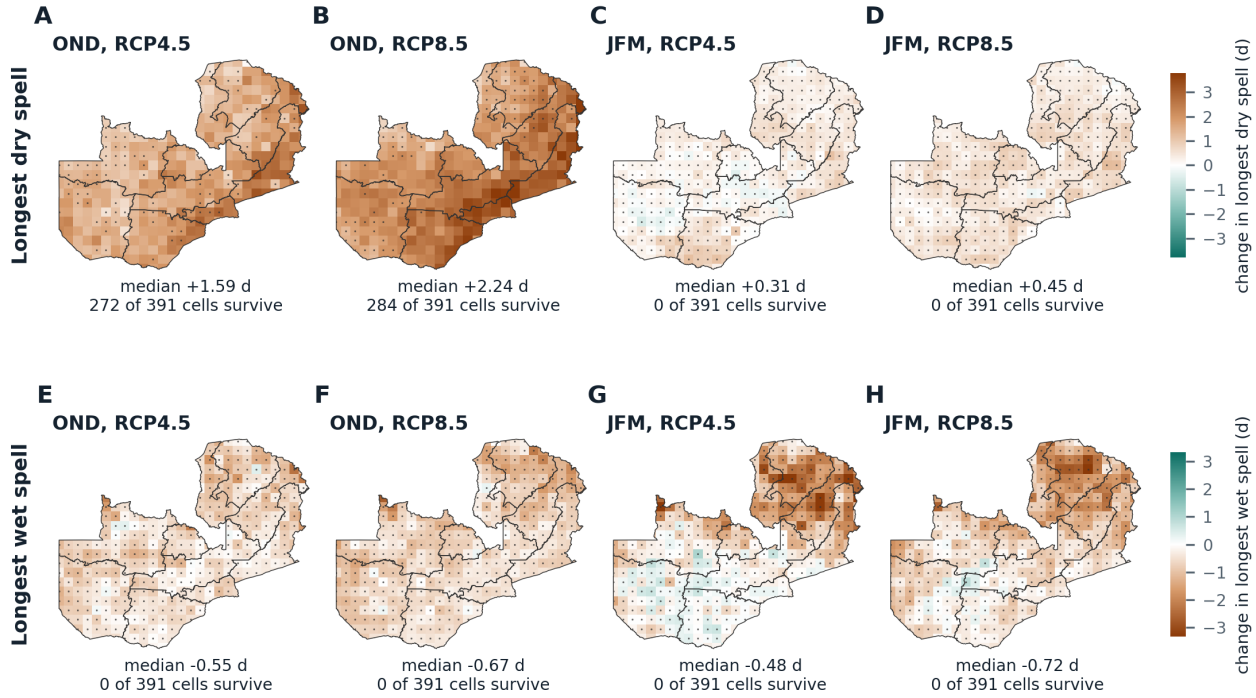


Fig 5. Projected change in the longest dry spell and wet spell, 2031–2060 minus 1981–2010. Ensemble median of all paired runs, in days, masked to Zambia, with province boundaries. (A–D) Longest dry spell (CDD); (E–H) longest wet spell (CWD); columns are October–December (OND) and January–March (JFM) under RCP4.5 and RCP8.5. Colours read the same way in both rows: brown is drier (a longer dry spell or a shorter wet spell), green wetter. Stippling marks cells whose change does not survive false-discovery-rate control across Zambia (Benjamini–Hochberg, $q = 0.10$); the text beneath each panel gives the Zambia median and the number of cells that survive.

(+2.73) provinces, against +1.72 to +1.86 days in Luapula, North-Western, Northern and Western (Table 3). Southern province, which lies largely in the drought-prone Region I, falls in between at +2.36 days but with the highest agreement of any province under RCP4.5 (90%). Provincial figures are reported with the effective number of cells behind them; Lusaka is resolved by fewer than ten effective cells at 0.44° and its value should be read as indicative. The wet spell shortens in every province under both scenarios, by 0.3 to 1.2 days, but agreement exceeds 90% only in Muchinga and Northern under RCP8.5, and it is not mapped as a result for the reasons given above. The loss of wet days has a different geography from the dry spell: it is largest in the west and south-west, -3.56 days in Western province and about -2.8 to -3.0 in Copperbelt, North-Western and Southern, and smallest in Northern and Luapula (-1.87 and -1.94 days). Both seasons and all five indices are given by province in S4 Table.

Table 3. Provincial change in the longest October–December dry and wet spells (days). Ensemble median of the province-weighted change per run, 2031–2060 minus 1981–2010, and the percentage of runs sharing its sign. Effective cells is the sum of cell-area fractions inside the province, weighted by the cosine of latitude.

Province	Effective cells	Dry spell (CDD)				Wet spell (CWD)			
		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
		Median	Agree	Median	Agree	Median	Agree	Median	Agree
Lusaka	9.6	+1.86	86%	+2.93	91%	−0.59	81%	−0.45	73%
Eastern	29.7	+1.82	81%	+2.90	91%	−0.48	81%	−0.75	77%
Muchinga	29.6	+1.59	81%	+2.89	82%	−0.53	86%	−0.96	91%
Central	40.9	+1.79	81%	+2.73	91%	−0.60	67%	−0.55	68%
Southern	37.3	+2.16	90%	+2.36	95%	−0.53	71%	−0.67	73%
Copperbelt	13.4	+1.46	86%	+2.17	95%	−0.52	76%	−0.82	68%
Northern	33.0	+1.54	76%	+1.86	77%	−0.87	76%	−1.24	91%
Western	55.5	+1.64	81%	+1.83	95%	−0.31	71%	−0.63	68%
North-Western	53.9	+1.17	86%	+1.76	100%	−0.68	67%	−0.85	77%
Luapula	21.3	+1.37	86%	+1.72	77%	−0.93	86%	−0.90	73%
Zambia	324.1	+1.65	95%	+2.23	95%	−0.66	81%	−0.75	91%

An independent ensemble at higher resolution

The CORDEX-CORE ensemble at 0.22° reproduces the observed dry spell considerably better than the primary ensemble. Its ten GCM-driven runs have OND dry-spell biases between -4.4 and $+3.9$ days (median -0.46), a spread of 8.3 days, against a spread of 22.1 days across the 25 runs at 0.44° (Fig 6). Without RegCM4-7 the seven remaining runs span 6.4 days (median $+0.43$). Pattern correlations are also more consistent: 0.79 to 0.88, or 0.84 to 0.88 without RegCM4-7. RegCM4-7 overestimates the longest OND wet spell by 8.6 to 10.7 days; the remap accounts for roughly one day of that. For the wet spell the two ensembles are equally spread (14.6 against 13.8 days), so the improvement is in the dry spell only.

Its projection agrees with the primary ensemble. The median OND dry-spell change under RCP8.5 is $+2.15$ days at 0.22° ($+2.06$ days without RegCM4-7) against $+2.23$ days at 0.44° . Two ensembles that share no regional model, sit on different grids and are compared against independently remapped observations differ by less than 0.2 days. Nine of the ten runs project a lengthening; the exception is CCLM5-0-15 driven by NorESM1-M (-1.6 days), and the three RegCM4-7 runs give $+2.1$ to $+4.9$ days. The single RCP4.5 run available at this resolution gives $+2.51$ days. The secondary ensemble also reproduces the loss of OND wet days, -4.1 days with all ten runs agreeing, and projects a lower OND seasonal total (-21 mm, 90% agreement) where the primary ensemble projects almost none. The JFM dry spell remains unreliable in both ensembles (70% agreement at 0.22° , 57% without RegCM4-7). One JFM result is new: all ten runs at 0.22° shorten the longest JFM wet spell (median -1.16 days), and its four regional-model families agree. But four families cannot give p below 0.125, and in the primary ensemble only 73% of runs agree and the regional-model families divide ($p = 1.000$), so it is not claimed as a robust change.

The limitation of the secondary ensemble must be stated as clearly as its agreement. With ten runs in four regional-model families, its member-

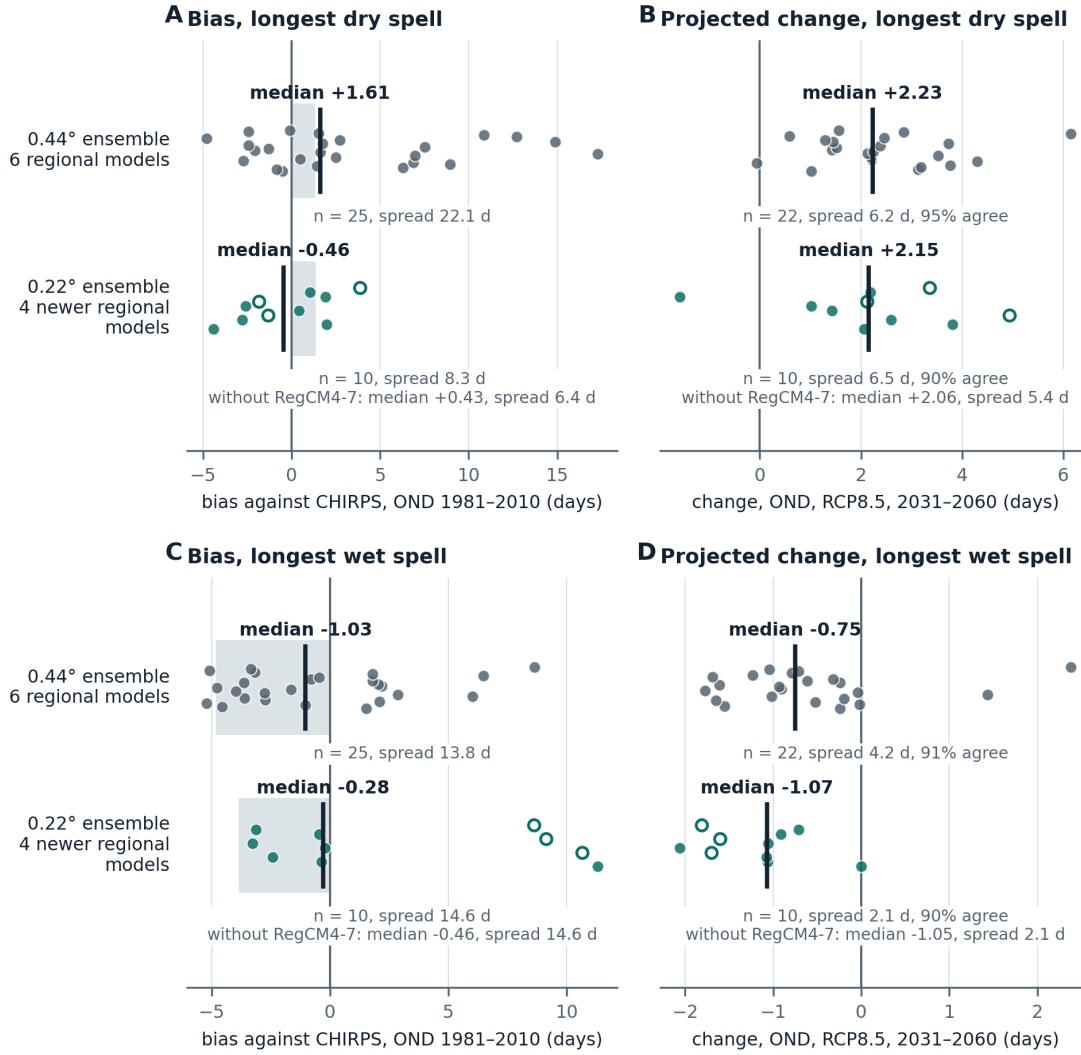


Fig 6. Two ensembles that share no regional model agree on the projection. GCM-driven runs of the 0.44° CORDEX-Africa ensemble (grey) and the 0.22° CORDEX-CORE ensemble (green), October–December (OND). (A) Bias in the mean longest dry spell against CHIRPS, 1981–2010, in days; the grey band spans the gap between CHIRPS and GPCC. (B) Projected change in the longest dry spell under RCP8.5, 2031–2060 minus 1981–2010, in days. (C, D) The same for the longest wet spell. Each dot is one run; vertical bars are ensemble medians. Open circles are RegCM4-7, the only model conservatively remapped to its ensemble’s grid; the 0.22° statistics without it are given beneath that row.

level sign test for the OND dry spell gives $p = 0.021$ ($p = 0.125$ without RegCM4-7), and its family-level test gives $p = 0.125$, the smallest value four families allow (0.250 with three). Per grid cell, the family-level test cannot reject anywhere at $q = 0.10$, with or without RegCM4-7. The secondary ensemble corroborates the magnitude and direction of the change; it does

not constitute a second significance test, and is not presented as one.

The reanalysis-driven runs at 0.22° reproduce the pattern found at 0.44° : their OND dry-spell biases, +4.9 (REMO2015), +6.7 (CCLM5-0-15) and +8.9 days (RegCM4-7), are larger than those of any GCM-driven run of the same regional models. Finding the same compensation in two independent ensembles indicates a property of the regional models rather than an accident of one ensemble. CanRCM4 provides the instructive exception: its wet-spell bias is +11.3 days driven by CanESM2 and +11.5 days driven by ERA-Interim, essentially unchanged by the driver. Where RCA4's dry bias was masked by a wet global model, CanRCM4's wet bias is the regional model's own and no driver conceals it.

Discussion

The central result is a lengthening of early-season dry spells over Zambia of about two days by the middle of this century, concentrated in October to December and largest in a central and eastern band, and it comes with a loss of early-season wet days rather than of rain. Its direction agrees with multi-model assessments over Southern Africa. Samuel et al. [23] found increasing CDD and decreasing CWD across the major Southern African river basins at global warming levels of 1.5, 2.0 and 3.0°C in CMIP5, CMIP6, CORDEX and CORDEX-CORE ensembles, and Maure et al. [21] projected longer dry spells and shorter wet spells across the region at 1.5 and 2.0°C . Pinto et al. [22] and Giorgi et al. [57] reported increases in CDD over Southern Africa by the end of the century under high emissions, New et al. [58] found a statistically significant increase in regionally averaged dry-spell duration over 1961–2000, and for Zambia itself Libanda and Ngonga [59] projected a significant increase in the maximum number of consecutive dry days from the middle of the century in five CMIP5 models, together with a decrease in the frequency and an increase in the intensity of rainfall. The first is found here as a robust loss of wet days; the second appears as more rain per wet day in most runs, but not robustly. The result is also consistent with reports of shortening rainy seasons through delayed onset and longer intra-seasonal dry spells [24, 26] and with observed increases in dry-spell frequency over Zambia [27]. What the present study adds is a mid-century magnitude computed per grid cell, evaluated on the index itself, tested in a way that respects model dependence, and mapped only where it survives a multiple-testing correction.

The contrast between the two seasons matches the current understanding of the region. In a recent review, Munday et al. [60] report improved confidence in projections of early-summer drying across southern Africa, arising from a delayed seasonal cycle and including more dry spells, and greater uncertainty in the core rainy season, partly because model biases in that season have grown worse through successive model generations. That is the pattern found here: a robust lengthening of the dry spell in October–December and no robust change in January–March. Shongwe et al. [61] projected a delayed onset of the rainy season across almost all of southern Africa and identified a reduction in moisture influx from the southwestern Indian Ocean during austral spring as a possible cause, although they also projected wetter conditions in the mean farther north, including parts of Zambia. Variability in the ENSO, the Indian Ocean Dipole and tropical Atlantic modulates dry and wet spells across the region [62, 63]. The present

analysis does not test these mechanisms, but the reanalysis-driven runs locate part of the model error. Driven by observed weather, all six regional models of the primary ensemble overestimate the OND dry spell, by 6.0 to 16.9 days, as do three of the four at 0.22° (by 4.9 to 8.9 days); the exception, CanRCM4, is too wet whatever drives it. A dry bias that appears when the driving circulation is realistic originates inside the regional models, where convection and the occurrence of light rain are parameterised. The wet-spell change, consistent across driving models but not across regional models, points to the same place.

Read against the agro-ecological regions (Fig 1), the provinces with the largest projected increases, Lusaka, Central, Eastern and Muchinga, lie mainly on the plateau of Region IIa, the country’s principal crop-producing region, and along the Luangwa valley arm of Region I. The smallest increases are in Luapula, Northern and North-Western, which lie in the high-rainfall Region III, and in Western province, which is mostly Region IIb. The change is therefore largest not where rainfall is scarcest but where most of the country’s rain-fed crops are grown. Provinces and agro-ecological regions do not coincide, and this reading is an interpretation of the provincial results rather than a separate analysis by region.

The agronomic significance of a two-day change lies in when it occurs. October to December spans land preparation, planting and emergence, when the crop is least tolerant of water stress; a lengthening of the longest dry spell in this window acts on the most vulnerable stage of the season [5, 6]. Chemura et al. [64] found that adding extreme indices, including consecutive dry days, to a maize suitability model for Southern Africa improved the model and showed more severe reductions in suitability than seasonal totals alone. This is nevertheless a statement about exposure, not about yield: the present analysis includes no soil-moisture, crop or hydrological model, and no yield inference is drawn from it.

Three methodological findings deserve emphasis because they bear on how such projections should be reported.

First, the treatment of model dependence changes the reported confidence substantially. The same data give $p < 0.001$ or $p = 0.062$ for the headline result depending on whether the 22 runs are treated as independent samples or first averaged within regional-model families. Since ten runs share RCA4, the member-level figure is not defensible as a measure of evidence. Reporting both, as done here, lets a reader see the cost of the assumption. The counterpart caveat is that family averaging gives each regional model equal weight, so a model represented by a single run counts as much as one represented by ten; neither convention is neutral, which is precisely why both are shown.

Second, the unit of testing and the correction for multiple testing together decide which maps carry a result. Of the twenty mapped panels (Fig 5 and S3 Fig), only those for the OND dry spell and OND wet days survive false-discovery-rate control in both scenarios, and they survive strongly. For the OND wet spell, a member-level test would mark 102 cells at $p < 0.05$ before correction and 83 after it, where the corrected family-level test marks none. Stippled maps are widely interpreted as showing where change is real [51], and without correction that interpretation is not warranted.

Third, observational uncertainty sets a floor on what counts as model error, as earlier evaluations of the CORDEX-Africa ensemble also found: the biases of the ensemble average were of similar magnitude to the differences

between observational datasets [13, 14]. CHIRPS and GPCC differ by 1.3 days in the mean OND dry spell and by 4.8 days in the mean wet spell over Zambia. The wet-spell disagreement exceeds any projected change in that index and exceeds the bias of 20 of the 25 GCM-driven runs, and the rain gauges show which product is nearer the truth: they side with GPCC, so CHIRPS, the primary reference for the dry spell, is not a safe reference for wet-spell length over Zambia. Reporting wet-spell biases as model deficiencies, or projected wet-spell changes as findings, would attribute to the models a difference that the observations themselves do not resolve. The dry spell, where only five runs come within that gap of CHIRPS, is the index on which these data can discriminate.

Several limitations remain. Spell indices are sensitive to grid scale, and although models and observations are compared on a common grid, 0.44° remains coarse relative to convective rainfall; the measured 1.1-day shift in the observed wet spell between the two grids quantifies this sensitivity directly. For the same reason RegCM4-7, the one remapped model, carries a wet-spell level about one day longer than on its native grid; its projected changes move by less than 0.2 days, and every 0.22° result is given with and without it. CHIRPS blends satellite estimates with gauges, and gauge density over Zambia is low, while GPCC’s gauge support is roughly 17 gauges nationally on a typical day; neither product is ground truth. The gauge check covers only 1981–1990 and 18 stations, because later station records in the public archive are too incomplete, and the stations may already contribute to both products. One ensemble member per GCM–RCM combination means internal variability is not separated from model differences. The simulations are CMIP5-driven, because downscaled CMIP6 projections for African domains were not available; the secondary ensemble addresses resolution and regional-model generation but not the generation of the driving global models. Finally, the analysis concerns the occurrence and amount of daily rainfall only: no soil-moisture, evaporation, crop or hydrological variable is included, and no rainfall extreme beyond the five indices.

Conclusion

Using 25 CORDEX-Africa simulations evaluated on the same indices they are used to project, this study finds that the longest dry spell of the October–December season over Zambia is projected to lengthen by about 2.2 days under RCP8.5 and 1.7 days under RCP4.5 by 2031–2060, with 95% of simulations agreeing on the direction and the signal surviving false-discovery-rate control over roughly seven tenths of the country. The increase is largest in Lusaka, Eastern, Muchinga and Central provinces, mainly on the plateau of agro-ecological Region IIa. Over the same season the number of wet days falls by 2.7 days under RCP8.5 and 2.0 days under RCP4.5 while the seasonal total barely changes, so early-season rain arrives on fewer days. The early-season wet spell shortens in most simulations, but the regional models disagree on it, and no robust change is found in the January–March season; neither is claimed as an established change. An independent ensemble at higher resolution, sharing no regional model with the primary one, reproduces the observed dry spell more closely and projects a comparable change of 2.15 days (2.06 days without its one remapped model).

For Zambian agriculture the practical implication concerns the distribution of rain within the season rather than its total: planning should anticipate longer dry spells in October to December, the period of planting and crop establishment. For the reporting of such projections, the analysis shows that conclusions about significance depend materially on how model dependence and multiple testing are handled, and that observational uncertainty should be quantified before model bias is interpreted. Three extensions would strengthen the result: analysing onset and cessation dates directly, repeating the analysis with CORDEX-CMIP6 simulations for Africa once they are published, and extending the gauge check beyond 1990 with station records from the Zambia Meteorological Department.

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Supporting information

S1 Fig. Ensemble spread and sign agreement. Longest October–December dry spell (A, B) and wet spell (C, D) under RCP8.5, 2031–2060 minus 1981–2010: (A, C) interquartile range of the change across runs, in days; (B, D) percentage of runs sharing the sign of the ensemble median.

S2 Fig. Gridded observations against rain gauges. Mean longest dry spell (A, B) and wet spell (C, D) at 18 Zambian stations (GHCN-Daily), October–December (A, C) and January–March (B, D), 1981–1990, against the same seasons in CHIRPS and GPCC at the station’s cell, on the 0.44° model grid (filled) and at native resolution (open). Days missing at the gauge are removed from the gridded series. The dashed line is equality.

S3 Fig. Projected change in wet days, rainfall per wet day and seasonal total, 2031–2060 minus 1981–2010. Ensemble median of all paired runs, masked to Zambia. (A–D) Number of wet days (days); (E–H) mean rainfall per wet day (mm day^{-1}); (I–L) seasonal total (mm); columns as in Fig 5. Brown is a decrease in every row. Stippling marks cells whose change does not survive false-discovery-rate control across Zambia (Benjamini–Hochberg, $q = 0.10$).

S1 Table. Ensemble inventory. Every GCM–RCM run of both ensembles, including the reanalysis-driven runs: code, institution, driving model, ensemble member, regional model and the experiments used.

S2 Table. Evaluation metrics for every run. Bias, spatial pattern correlation, interannual variability ratio and, for reanalysis-driven runs, in-

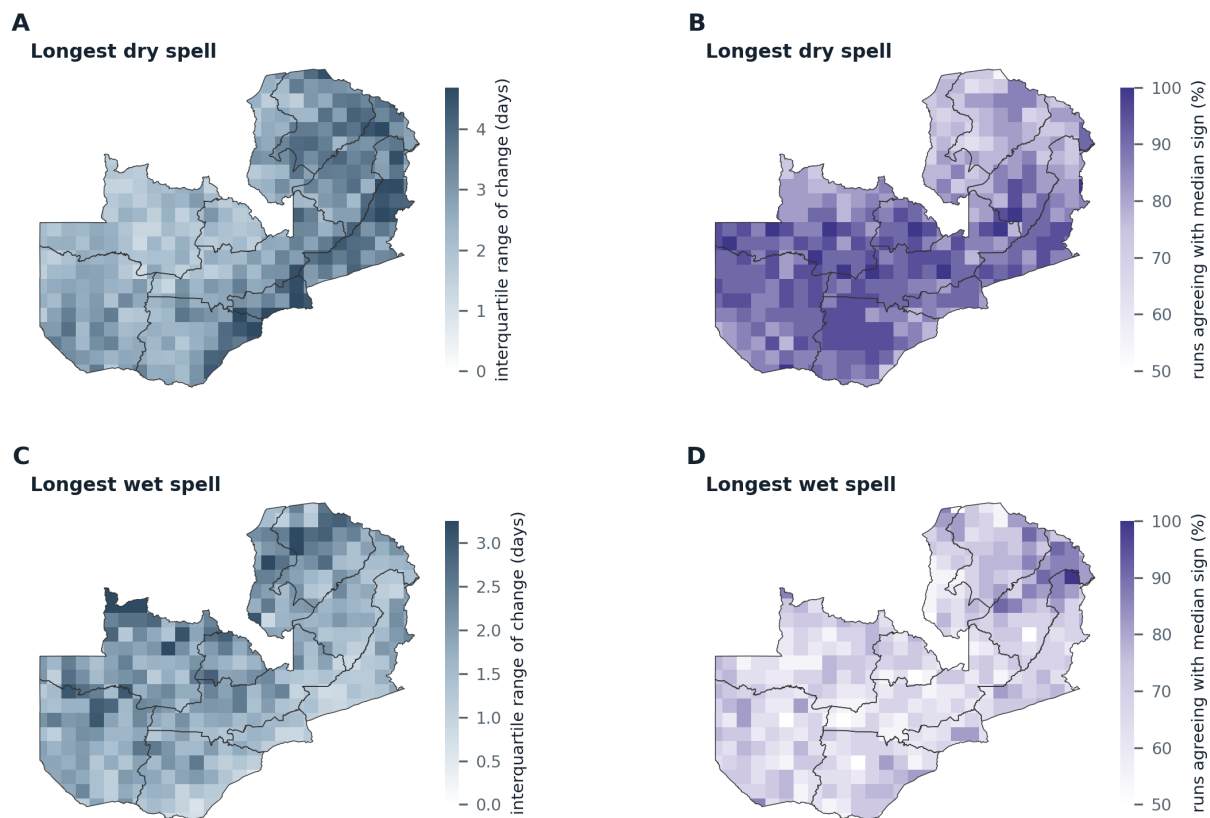
terannual correlation, for all five indices and both seasons, against CHIRPS and against GPCC, on both grids.

S3 Table. Per-run projected changes. Change in each index for every paired run, both scenarios, both seasons and both grids.

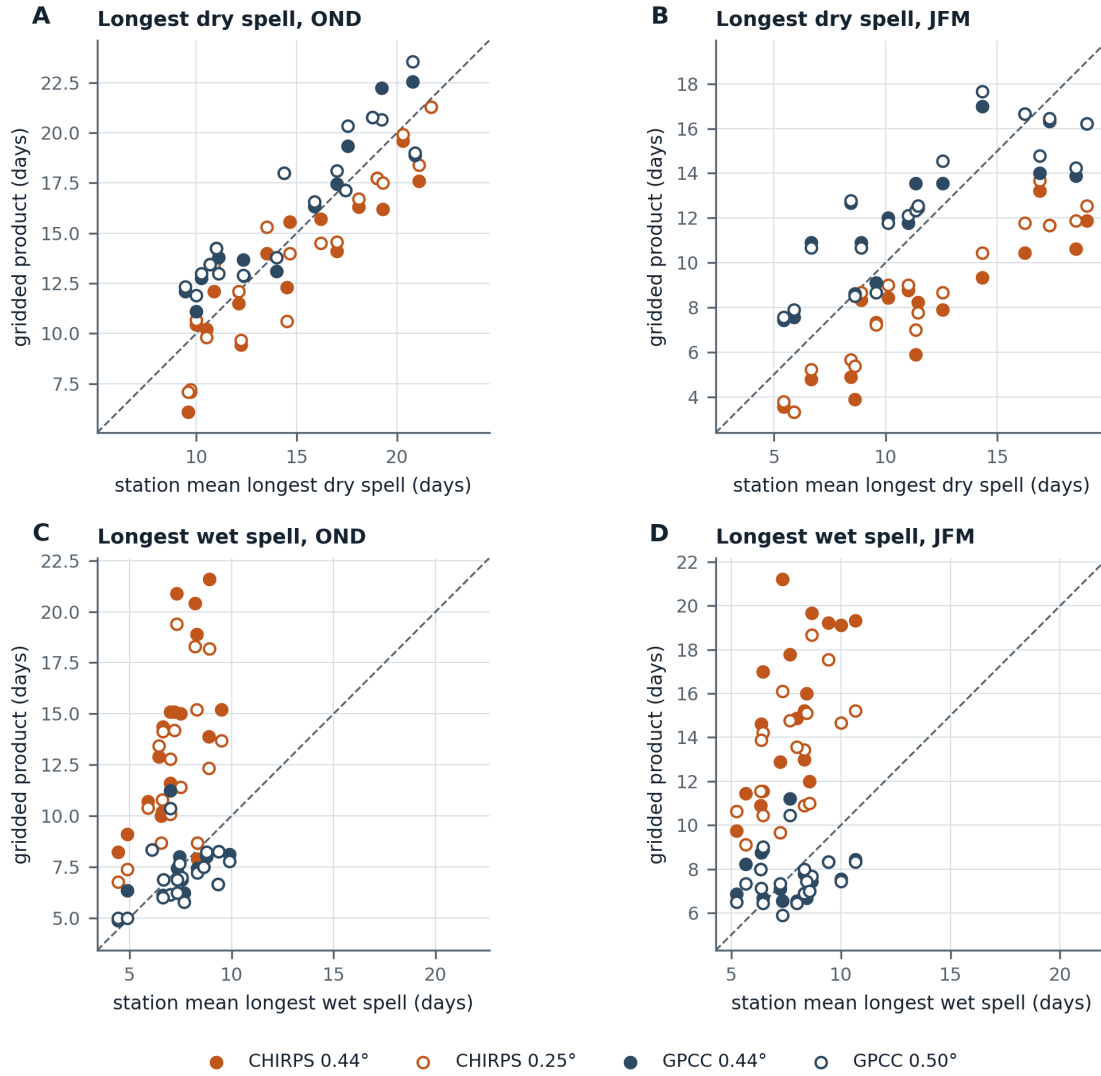
S4 Table. Provincial changes with cell counts. Ensemble median, interquartile range and agreement for every province, all five indices, both seasons and both scenarios.

Supporting information

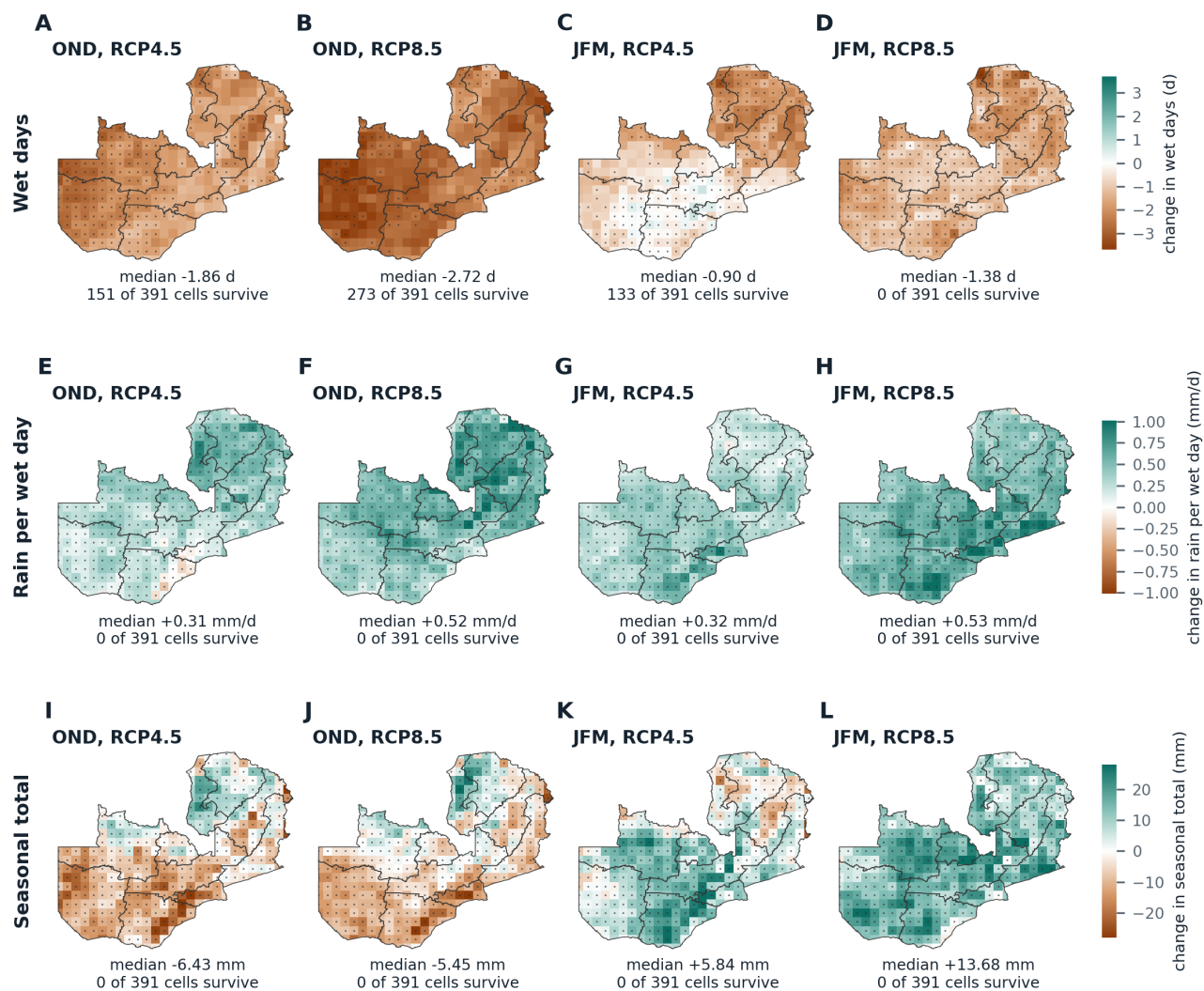
The complete tables, with every metric, are the Excel workbooks S1–S4 Table, deposited with the code and data at Zenodo ([doi:10.5281/zenodo.22944022](https://doi.org/10.5281/zenodo.22944022)).



S1 Fig. Ensemble spread and sign agreement. Longest October–December dry spell (A, B) and wet spell (C, D) under RCP8.5: (A, C) interquartile range of the change across runs (days); (B, D) percentage of runs sharing the sign of the median.



S2 Fig. Gridded observations against rain gauges. Mean longest dry spell (A, B) and wet spell (C, D) at 18 Zambian stations (GHCN-Daily), 1981–1990, against CHIRPS and GPCC at the station's cell, on the 0.44° model grid (filled) and at native resolution (open). The dashed line is equality.



S3 Fig. Projected change in wet days, rainfall per wet day and seasonal total, 2031–2060 minus 1981–2010. (A–D) wet days; (E–H) mean rainfall per wet day; (I–L) seasonal total. Brown is a decrease. Stippling marks cells whose change does not survive false-discovery-rate control.

S1 Table. Ensemble inventory. Every run of both ensembles, including the reanalysis-driven runs. Baseline: 1981–2010; rcp45/rcp85: 2031–2060.

Code	Grid	Regional model	Driving model	Member	Institution	Periods
M1	AFR-44	CRCM5	CanESM2	r1i1p1	UQAM	baseline, rcp45
M2	AFR-44	RCA4	CanESM2	r1i1p1	SMHI	baseline, rcp45, rcp85
M3	AFR-44	CCLM4-8-17	CNRM-CM5	r1i1p1	CLMcom	baseline, rcp45, rcp85
M4	AFR-44	RCA4	CNRM-CM5	r1i1p1	SMHI	baseline, rcp45, rcp85
M5	AFR-44	RCA4	CSIRO-Mk3-6-0	r1i1p1	SMHI	baseline, rcp45, rcp85
M6	AFR-44	CCLM4-8-17	EC-EARTH	r12i1p1	CLMcom	baseline, rcp45, rcp85
M7	AFR-44	HIRHAM5	EC-EARTH	r3i1p1	DMI	baseline, rcp45, rcp85
M8	AFR-44	REMO2009	EC-EARTH	r12i1p1	MPI-CSC	baseline, rcp45, rcp85
M9	AFR-44	RACMO22T	EC-EARTH	r1i1p1	KNMI	baseline, rcp45, rcp85
M10	AFR-44	RCA4	EC-EARTH	r12i1p1	SMHI	baseline, rcp45, rcp85
M11	AFR-44	REMO2009	IPSL-CM5A-LR	r1i1p1	GERICS	baseline, rcp85
M12	AFR-44	RCA4	IPSL-CM5A-MR	r1i1p1	SMHI	baseline, rcp45, rcp85
M13	AFR-44	REMO2009	MIROC5	r1i1p1	GERICS	baseline, rcp85
M14	AFR-44	RCA4	MIROC5	r1i1p1	SMHI	baseline, rcp45, rcp85
M15	AFR-44	CCLM4-8-17	HadGEM2-ES	r1i1p1	CLMcom	baseline, rcp45, rcp85
M16	AFR-44	REMO2009	HadGEM2-ES	r1i1p1	GERICS	baseline, rcp85
M17	AFR-44	RACMO22T	HadGEM2-ES	r1i1p1	KNMI	baseline, rcp45, rcp85
M18	AFR-44	RCA4	HadGEM2-ES	r1i1p1	SMHI	baseline, rcp45, rcp85
M19	AFR-44	CCLM4-8-17	MPI-ESM-LR	r1i1p1	CLMcom	baseline, rcp45, rcp85
M20	AFR-44	CRCM5	MPI-ESM-LR	r1i1p1	UQAM	baseline, rcp45
M21	AFR-44	REMO2009	MPI-ESM-LR	r1i1p1	MPI-CSC	baseline, rcp45, rcp85
M22	AFR-44	RCA4	MPI-ESM-LR	r1i1p1	SMHI	baseline, rcp45, rcp85
M24	AFR-44	RCA4	NorESM1-M	r1i1p1	SMHI	baseline, rcp45, rcp85
M25	AFR-44	REMO2009	GFDL-ESM2G	r1i1p1	GERICS	baseline
M26	AFR-44	RCA4	GFDL-ESM2M	r1i1p1	SMHI	baseline, rcp45, rcp85
C-HadGEM2-CCLM5-0-15	AFR-22	CCLM5-0-15	HadGEM2-ES	r1i1p1	CLMcom-KIT	baseline, rcp85
C-MPIESM-LR-CCLM5-0-15	AFR-22	CCLM5-0-15	MPI-ESM-LR	r1i1p1	CLMcom-KIT	baseline, rcp85
C-NorESM1-CCLM5-0-15	AFR-22	CCLM5-0-15	NorESM1-M	r1i1p1	CLMcom-KIT	baseline, rcp85
C-HadGEM2-REMO2015	AFR-22	REMO2015	HadGEM2-ES	r1i1p1	GERICS	baseline, rcp85
C-MPIESM-LR-REMO2015	AFR-22	REMO2015	MPI-ESM-LR	r1i1p1	GERICS	baseline, rcp85
C-NorESM1-REMO2015	AFR-22	REMO2015	NorESM1-M	r1i1p1	GERICS	baseline, rcp85
C-CanESM2-CanRCM4	AFR-22	CanRCM4	CanESM2	r1i1p1	CCCma	baseline, rcp45, rcp85
C-HadGEM2-RegCM4-7	AFR-22	RegCM4-7	HadGEM2-ES	r1i1p1	ICTP	baseline, rcp85
C-MPIESM-MR-RegCM4-7	AFR-22	RegCM4-7	MPI-ESM-MR	r1i1p1	ICTP	baseline, rcp85
C-NorESM1-RegCM4-7	AFR-22	RegCM4-7	NorESM1-M	r1i1p1	ICTP	baseline, rcp85
C-ERAINT-CCLM5-0-15	AFR-22	CCLM5-0-15	ERA-Interim	r1i1p1	CLMcom-KIT	evaluation
C-ERAINT-REMO2015	AFR-22	REMO2015	ERA-Interim	r1i1p1	GERICS	evaluation
C-ERAINT-RegCM4-7	AFR-22	RegCM4-7	ERA-Interim	r1i1p1	ICTP	evaluation
C-ERAINT-CanRCM4	AFR-22	CanRCM4	ERA-Interim	r1i1p1	CCCma	evaluation
E-CLMcom-CCLM4-8-17	AFR-44	CCLM4-8-17	ERA-Interim	r1i1p1	CLMcom	evaluation
E-DMI-HIRHAM5	AFR-44	HIRHAM5	ERA-Interim	r1i1p1	DMI	evaluation
E-KNMI-RACMO22T	AFR-44	RACMO22T	ERA-Interim	r1i1p1	KNMI	evaluation
E-MPI-CSC-REMO2009	AFR-44	REMO2009	ERA-Interim	r1i1p1	MPI-CSC	evaluation
E-SMHI-RCA4	AFR-44	RCA4	ERA-Interim	r1i1p1	SMHI	evaluation
E-UQAM-CRCM5	AFR-44	CRCM5	ERA-Interim	r1i1p1	UQAM	evaluation

S2 Table (extract). Bias of every run against CHIRPS, 1981–2010. Zambia-weighted model minus CHIRPS: CDD, CWD, RR1 in days; SDII in mm day^{−1}; PRCPTOT in mm. r is the spatial pattern correlation of the mean CDD. The workbook adds GPCC and the variability metrics.

Run	Grid (°)	Season	CDD	CWD	RR1	SDII	PRCPTOT	r (CDD)
CCLM4-8-17 / CNRM-CM5 (M3)	0.44	OND	+2.72	−0.46	−0.10	+1.78	+74	0.88
CCLM4-8-17 / CNRM-CM5 (M3)	0.44	JFM	−0.88	+1.33	+3.72	−0.71	−15	0.31
CCLM4-8-17 / EC-EARTH (M6)	0.44	OND	+10.87	−3.17	−11.19	+1.77	−34	0.88
CCLM4-8-17 / EC-EARTH (M6)	0.44	JFM	+1.76	+2.82	−1.04	+0.50	+20	0.89
CCLM4-8-17 / ERA-Interim	0.44	OND	+16.94	−4.59	−18.50	+1.72	−102	0.84
CCLM4-8-17 / ERA-Interim	0.44	JFM	+7.91	+1.01	−11.31	+0.05	−102	0.85

Run	Grid (°)	Season	CDD	CWD	RR1	SDII	PRCPTOT	<i>r</i> (CDD)
CCLM4-8-17 / HadGEM2-ES (M15)	0.44	OND	+6.88	-2.73	-9.82	+2.22	-8	0.88
CCLM4-8-17 / HadGEM2-ES (M15)	0.44	JFM	+5.56	+1.43	-8.64	-0.14	-93	0.73
CCLM4-8-17 / MPI-ESM-LR (M19)	0.44	OND	+6.97	-2.75	-8.59	+2.24	+5	0.91
CCLM4-8-17 / MPI-ESM-LR (M19)	0.44	JFM	+2.46	-0.55	-4.86	+0.31	-31	0.89
CRCM5 / CanESM2 (M1)	0.44	OND	+17.27	-3.96	-14.34	+1.71	-60	0.74
CRCM5 / CanESM2 (M1)	0.44	JFM	+10.97	-6.46	-20.36	+0.51	-162	0.94
CRCM5 / ERA-Interim	0.44	OND	+16.77	-2.27	-10.53	+1.70	-29	0.57
CRCM5 / ERA-Interim	0.44	JFM	+1.31	-2.30	-4.79	+0.84	+8	0.92
CRCM5 / MPI-ESM-LR (M20)	0.44	OND	+1.61	-1.64	+0.61	+2.08	+99	0.44
CRCM5 / MPI-ESM-LR (M20)	0.44	JFM	+0.66	-3.58	-4.09	+0.12	-32	0.92
HIRHAM5 / EC-EARTH (M7)	0.44	OND	+1.52	-5.08	-6.90	+0.83	-18	0.76
HIRHAM5 / EC-EARTH (M7)	0.44	JFM	+0.18	-6.29	-7.63	-0.28	-78	0.58
HIRHAM5 / ERA-Interim	0.44	OND	+13.93	-6.84	-17.40	+1.21	-103	0.79
HIRHAM5 / ERA-Interim	0.44	JFM	+5.38	-8.51	-18.85	-0.27	-183	0.44
RACMO22T / EC-EARTH (M9)	0.44	OND	-0.10	+8.63	+8.75	-0.15	+59	0.89
RACMO22T / EC-EARTH (M9)	0.44	JFM	+0.74	+20.60	+8.12	-1.33	-20	0.19
RACMO22T / ERA-Interim	0.44	OND	+8.92	+3.90	-3.80	-0.59	-58	0.91
RACMO22T / ERA-Interim	0.44	JFM	+6.99	+8.72	-5.79	-2.00	-170	0.28
RACMO22T / HadGEM2-ES (M17)	0.44	OND	+0.49	+6.01	+4.20	-0.45	+9	0.86
RACMO22T / HadGEM2-ES (M17)	0.44	JFM	+4.82	+12.38	-0.00	-1.56	-100	0.31
RCA4 / CNRM-CM5 (M4)	0.44	OND	-4.80	+6.49	+12.81	+1.75	+207	0.63
RCA4 / CNRM-CM5 (M4)	0.44	JFM	-0.25	+9.31	+5.06	-0.59	+10	0.53
RCA4 / CSIRO-Mk3-6-0 (M5)	0.44	OND	+12.71	+1.80	-3.64	+1.86	+47	0.82
RCA4 / CSIRO-Mk3-6-0 (M5)	0.44	JFM	+8.11	+0.01	-13.15	+0.33	-104	0.78
RCA4 / CanESM2 (M2)	0.44	OND	+14.88	-0.80	-8.23	+2.75	+29	0.83
RCA4 / CanESM2 (M2)	0.44	JFM	+9.19	-1.99	-16.77	+0.84	-113	0.81
RCA4 / EC-EARTH (M10)	0.44	OND	-0.54	+1.54	+4.43	+2.06	+136	0.73
RCA4 / EC-EARTH (M10)	0.44	JFM	+1.78	+3.92	-0.36	+0.43	+27	0.83
RCA4 / ERA-Interim	0.44	OND	+13.09	-0.78	-7.96	+1.99	+9	0.76
RCA4 / ERA-Interim	0.44	JFM	+4.66	+2.22	-7.18	+0.74	-21	0.85
RCA4 / GFDL-ESM2M (M26)	0.44	OND	+1.75	+1.79	+2.42	+2.05	+115	0.71
RCA4 / GFDL-ESM2M (M26)	0.44	JFM	+1.23	+3.62	-0.21	-0.29	-21	0.81
RCA4 / HadGEM2-ES (M18)	0.44	OND	+2.48	+2.86	+2.28	+2.41	+130	0.74
RCA4 / HadGEM2-ES (M18)	0.44	JFM	+3.91	+3.62	-5.63	+0.41	-27	0.87
RCA4 / IPSL-CM5A-MR (M12)	0.44	OND	+6.29	-1.03	-4.39	+3.07	+82	0.79
RCA4 / IPSL-CM5A-MR (M12)	0.44	JFM	+8.85	-4.95	-19.51	+0.52	-162	0.85
RCA4 / MIROC5 (M14)	0.44	OND	+8.95	+2.10	-2.30	+1.41	+46	0.74
RCA4 / MIROC5 (M14)	0.44	JFM	+2.39	+7.44	-0.98	+0.85	+49	0.74
RCA4 / MPI-ESM-LR (M22)	0.44	OND	-1.31	+2.19	+6.56	+2.65	+189	0.76
RCA4 / MPI-ESM-LR (M22)	0.44	JFM	+1.40	+2.84	-1.69	+0.35	+9	0.85
RCA4 / NorESM1-M (M24)	0.44	OND	+7.53	+2.04	+0.00	+1.94	+88	0.81
RCA4 / NorESM1-M (M24)	0.44	JFM	+3.16	+5.40	-1.38	+0.51	+23	0.79
REMO2009 / EC-EARTH (M8)	0.44	OND	-2.43	-3.34	-0.32	+1.83	+73	0.87
REMO2009 / EC-EARTH (M8)	0.44	JFM	+0.45	-6.46	-7.66	+0.85	-28	0.81
REMO2009 / ERA-Interim	0.44	OND	+6.01	-5.65	-12.33	+1.18	-60	0.84
REMO2009 / ERA-Interim	0.44	JFM	+5.00	-9.32	-19.93	+0.92	-153	0.65
REMO2009 / GFDL-ESM2G (M25)	0.44	OND	-2.43	-3.62	-1.08	+2.38	+99	0.73
REMO2009 / GFDL-ESM2G (M25)	0.44	JFM	+0.45	-7.49	-9.65	+1.15	-28	0.77
REMO2009 / HadGEM2-ES (M16)	0.44	OND	-2.74	-3.60	-0.91	+2.57	+106	0.83
REMO2009 / HadGEM2-ES (M16)	0.44	JFM	+2.59	-7.59	-12.70	+1.49	-43	0.83
REMO2009 / IPSL-CM5A-LR (M11)	0.44	OND	-0.85	-4.54	-5.08	+2.62	+62	0.70
REMO2009 / IPSL-CM5A-LR (M11)	0.44	JFM	+3.66	-8.28	-16.53	+1.89	-67	0.81
REMO2009 / MIROC5 (M13)	0.44	OND	+1.42	-5.20	-8.56	+0.95	-30	0.80
REMO2009 / MIROC5 (M13)	0.44	JFM	+2.30	-5.57	-9.83	+1.07	-36	0.77
REMO2009 / MPI-ESM-LR (M21)	0.44	OND	-2.09	-4.76	-2.26	+2.17	+69	0.86
REMO2009 / MPI-ESM-LR (M21)	0.44	JFM	+2.26	-7.51	-12.26	+1.12	-59	0.86
CCLM5-0-15 / ERA-Interim	0.22	OND	+6.67	-1.06	-6.31	+1.19	-17	0.93
CCLM5-0-15 / ERA-Interim	0.22	JFM	+4.45	+1.12	-7.57	-0.84	-124	0.93
CCLM5-0-15 / HadGEM2-ES	0.22	OND	+1.98	-0.36	-4.25	+1.24	+8	0.88
CCLM5-0-15 / HadGEM2-ES	0.22	JFM	+4.16	-0.51	-9.21	-1.42	-171	0.87
CCLM5-0-15 / MPI-ESM-LR	0.22	OND	+0.43	-0.21	-1.74	+1.58	+43	0.87
CCLM5-0-15 / MPI-ESM-LR	0.22	JFM	+3.17	+0.72	-4.93	-0.47	-82	0.95
CCLM5-0-15 / NorESM1-M	0.22	OND	+1.92	-0.46	-3.58	+0.48	-13	0.87
CCLM5-0-15 / NorESM1-M	0.22	JFM	+1.57	+5.79	+0.25	-0.62	-38	0.89
CanRCM4 / CanESM2	0.22	OND	-4.40	+11.30	+16.87	+1.01	+197	0.86

Run	Grid (°)	Season	CDD	CWD	RR1	SDII	PRCPTOT	<i>r</i> (CDD)
CanRCM4 / CanESM2	0.22	JFM	+2.56	+12.52	+2.53	+0.64	+68	0.83
CanRCM4 / ERA-Interim	0.22	OND	−2.44	+11.50	+14.06	+0.19	+126	0.87
CanRCM4 / ERA-Interim	0.22	JFM	+0.98	+13.97	+6.22	−0.34	+36	0.70
REMO2015 / ERA-Interim	0.22	OND	+4.86	−4.99	−9.28	+0.22	−67	0.88
REMO2015 / ERA-Interim	0.22	JFM	+3.25	−6.61	−14.29	+0.20	−131	0.67
REMO2015 / HadGEM2-ES	0.22	OND	−2.80	−2.41	+1.29	+1.98	+99	0.87
REMO2015 / HadGEM2-ES	0.22	JFM	+1.80	−5.73	−9.19	+0.68	−52	0.79
REMO2015 / MPI-ESM-LR	0.22	OND	−2.61	−3.26	+1.09	+1.63	+80	0.85
REMO2015 / MPI-ESM-LR	0.22	JFM	+1.22	−5.73	−8.30	+0.41	−61	0.74
REMO2015 / NorESM1-M	0.22	OND	+1.04	−3.12	−3.95	+1.05	+10	0.84
REMO2015 / NorESM1-M	0.22	JFM	−0.05	−4.83	−6.02	+0.88	−10	0.62
RegCM4-7 / ERA-Interim	0.22	OND	+8.90	+6.51	−1.16	+0.59	+19	0.72
RegCM4-7 / ERA-Interim	0.22	JFM	+0.02	+20.46	+8.26	+0.46	+112	0.84
RegCM4-7 / HadGEM2-ES	0.22	OND	−1.34	+10.66	+10.82	+2.29	+207	0.81
RegCM4-7 / HadGEM2-ES	0.22	JFM	−1.85	+23.54	+13.14	+1.44	+230	0.87
RegCM4-7 / MPI-ESM-MR	0.22	OND	−1.86	+9.12	+11.54	+2.22	+212	0.79
RegCM4-7 / MPI-ESM-MR	0.22	JFM	−1.55	+17.55	+11.24	+1.08	+185	0.84
RegCM4-7 / NorESM1-M	0.22	OND	+3.86	+8.62	+4.13	+0.41	+59	0.85
RegCM4-7 / NorESM1-M	0.22	JFM	−1.55	+22.97	+12.26	+0.52	+159	0.79

S3 Table. Projected change for every run, OND, 2031–2060 minus 1981–2010. Units as in S2 Table.

Run	Grid (°)	Scenario	CDD	CWD	RR1	SDII	PRCPTOT
CCLM4-8-17 / CNRM-CM5 (M3)	0.44	RCP8.5	+1.44	−0.32	−2.14	+0.32	−9
CCLM4-8-17 / EC-EARTH (M6)	0.44	RCP8.5	+0.58	−0.79	−3.00	+0.38	−17
CCLM4-8-17 / HadGEM2-ES (M15)	0.44	RCP8.5	+4.30	−0.20	−3.84	−0.01	−34
CCLM4-8-17 / MPI-ESM-LR (M19)	0.44	RCP8.5	+2.13	−1.78	−5.97	+0.65	−41
HIRHAM5 / EC-EARTH (M7)	0.44	RCP8.5	+6.15	−0.71	−3.28	+0.40	−18
RACMO22T / EC-EARTH (M9)	0.44	RCP8.5	+1.56	+2.38	−0.28	−0.01	−3
RACMO22T / HadGEM2-ES (M17)	0.44	RCP8.5	+2.19	+1.44	−0.81	−0.06	−7
RCA4 / CNRM-CM5 (M4)	0.44	RCP8.5	+1.28	−1.69	−2.20	+0.37	−3
RCA4 / CSIRO-Mk3-6-0 (M5)	0.44	RCP8.5	+2.46	−1.23	−2.66	+0.63	−2
RCA4 / CanESM2 (M2)	0.44	RCP8.5	+3.73	−0.61	−2.21	+0.58	+1
RCA4 / EC-EARTH (M10)	0.44	RCP8.5	+1.02	−0.24	−2.57	+0.91	+14
RCA4 / GFDL-ESM2M (M26)	0.44	RCP8.5	+2.37	−0.24	−1.81	+0.88	+20
RCA4 / HadGEM2-ES (M18)	0.44	RCP8.5	+3.53	−0.04	−2.68	+0.63	+3
RCA4 / IPSL-CM5A-MR (M12)	0.44	RCP8.5	+3.19	−0.02	−1.99	+1.07	+19
RCA4 / MIROC5 (M14)	0.44	RCP8.5	−0.07	−1.65	−0.81	+0.92	+27
RCA4 / MPI-ESM-LR (M22)	0.44	RCP8.5	+1.43	−0.93	−3.07	+0.19	−24
RCA4 / NorESM1-M (M24)	0.44	RCP8.5	+1.52	−1.61	−1.74	+0.74	+14
REMO2009 / EC-EARTH (M8)	0.44	RCP8.5	+2.85	−1.04	−3.32	+1.13	+15
REMO2009 / HadGEM2-ES (M16)	0.44	RCP8.5	+2.21	−1.02	−4.26	+0.34	−28
REMO2009 / IPSL-CM5A-LR (M11)	0.44	RCP8.5	+3.13	−1.55	−5.12	+0.42	−39
REMO2009 / MIROC5 (M13)	0.44	RCP8.5	+3.77	−0.52	−2.75	+0.64	−2
REMO2009 / MPI-ESM-LR (M21)	0.44	RCP8.5	+2.24	−0.90	−4.31	+0.64	−18
CCLM4-8-17 / CNRM-CM5 (M3)	0.44	RCP4.5	+3.36	−0.80	−4.23	+0.10	−37
CCLM4-8-17 / EC-EARTH (M6)	0.44	RCP4.5	+0.16	+0.55	−0.83	+0.19	−2
CCLM4-8-17 / HadGEM2-ES (M15)	0.44	RCP4.5	+2.29	−0.03	−2.20	+0.44	−6
CCLM4-8-17 / MPI-ESM-LR (M19)	0.44	RCP4.5	+1.85	−0.88	−3.62	+0.40	−25
CRCM5 / CanESM2 (M1)	0.44	RCP4.5	+6.59	−0.91	−1.93	+0.17	−10
CRCM5 / MPI-ESM-LR (M20)	0.44	RCP4.5	+0.91	−0.39	−1.08	+0.12	−0
HIRHAM5 / EC-EARTH (M7)	0.44	RCP4.5	+2.77	−0.56	−2.17	+0.31	−9
RACMO22T / EC-EARTH (M9)	0.44	RCP4.5	+1.44	+0.24	−0.61	−0.06	−8
RACMO22T / HadGEM2-ES (M17)	0.44	RCP4.5	+1.43	+0.98	+0.26	−0.05	+1
RCA4 / CNRM-CM5 (M4)	0.44	RCP4.5	+0.89	−1.53	−2.20	+0.27	−9
RCA4 / CSIRO-Mk3-6-0 (M5)	0.44	RCP4.5	+3.16	−1.40	−4.45	+0.30	−33
RCA4 / CanESM2 (M2)	0.44	RCP4.5	+2.06	−1.06	−1.50	+0.57	+4
RCA4 / EC-EARTH (M10)	0.44	RCP4.5	+1.29	+0.25	−0.71	+0.75	+29
RCA4 / GFDL-ESM2M (M26)	0.44	RCP4.5	+1.65	−0.66	−1.88	+0.47	+3
RCA4 / HadGEM2-ES (M18)	0.44	RCP4.5	+3.11	−0.18	−2.27	+0.64	+4

Run	Grid (°)	Scenario	CDD	CWD	RR1	SDII	PRCPTOT
RCA4 / IPSL-CM5A-MR (M12)	0.44	RCP4.5	+2.73	−0.58	−2.20	+0.50	−4
RCA4 / MIROC5 (M14)	0.44	RCP4.5	−2.94	−1.34	+0.11	+1.02	+43
RCA4 / MPI-ESM-LR (M22)	0.44	RCP4.5	+0.76	−0.23	−2.03	+0.10	−15
RCA4 / NorESM1-M (M24)	0.44	RCP4.5	+0.75	−1.77	−2.43	+0.34	−9
REMO2009 / EC-EARTH (M8)	0.44	RCP4.5	+1.85	−0.70	−1.30	+0.65	+15
REMO2009 / MPI-ESM-LR (M21)	0.44	RCP4.5	+0.51	−0.81	−2.51	+0.25	−15
CCLM5-0-15 / HadGEM2-ES	0.22	RCP8.5	+3.81	−1.06	−4.55	−0.18	−48
CCLM5-0-15 / MPI-ESM-LR	0.22	RCP8.5	+1.42	−2.06	−3.71	−0.17	−39
CCLM5-0-15 / NorESM1-M	0.22	RCP8.5	−1.58	−0.92	−0.17	−0.27	−14
CanRCM4 / CanESM2	0.22	RCP8.5	+2.06	+0.00	−1.98	+0.48	+11
REMO2015 / HadGEM2-ES	0.22	RCP8.5	+2.60	−1.08	−4.67	+0.65	−18
REMO2015 / MPI-ESM-LR	0.22	RCP8.5	+1.02	−1.05	−3.98	+0.77	−10
REMO2015 / NorESM1-M	0.22	RCP8.5	+2.19	−0.71	−2.80	+0.73	−1
RegCM4-7 / HadGEM2-ES	0.22	RCP8.5	+4.94	−1.70	−6.82	−0.93	−107
RegCM4-7 / MPI-ESM-MR	0.22	RCP8.5	+2.12	−1.61	−4.52	+0.54	−24
RegCM4-7 / NorESM1-M	0.22	RCP8.5	+3.35	−1.81	−4.24	+0.32	−25
CanRCM4 / CanESM2	0.22	RCP4.5	+2.51	−1.28	−3.02	+0.38	−3

S3 Table (continued). Projected change for every run, JFM, 2031–2060 minus 1981–2010. Units as in S2 Table.

Run	Grid (°)	Scenario	CDD	CWD	RR1	SDII	PRCPTOT
CCLM4-8-17 / CNRM-CM5 (M3)	0.44	RCP8.5	−0.34	+0.46	+0.54	−0.01	+5
CCLM4-8-17 / EC-EARTH (M6)	0.44	RCP8.5	+0.35	+0.79	−1.30	+0.12	−5
CCLM4-8-17 / HadGEM2-ES (M15)	0.44	RCP8.5	−0.37	+3.70	+3.43	+0.26	+44
CCLM4-8-17 / MPI-ESM-LR (M19)	0.44	RCP8.5	+1.07	+0.02	−2.66	+0.32	−9
HIRHAM5 / EC-EARTH (M7)	0.44	RCP8.5	+1.25	−0.45	−2.54	+0.38	−3
RACMO22T / EC-EARTH (M9)	0.44	RCP8.5	−1.68	+1.21	+2.25	−0.20	+4
RACMO22T / HadGEM2-ES (M17)	0.44	RCP8.5	+0.02	+1.85	+0.34	−0.02	+2
RCA4 / CNRM-CM5 (M4)	0.44	RCP8.5	+1.19	−1.37	−1.66	+0.17	−2
RCA4 / CSIRO-Mk3-6-0 (M5)	0.44	RCP8.5	+1.37	−0.89	−1.69	+0.92	+31
RCA4 / CanESM2 (M2)	0.44	RCP8.5	+0.53	−0.67	+0.58	+0.92	+47
RCA4 / EC-EARTH (M10)	0.44	RCP8.5	−0.45	−0.95	−0.66	+0.62	+32
RCA4 / GFDL-ESM2M (M26)	0.44	RCP8.5	+0.49	−2.71	−2.78	+0.56	+7
RCA4 / HadGEM2-ES (M18)	0.44	RCP8.5	−0.29	−0.81	+0.78	+0.63	+46
RCA4 / IPSL-CM5A-MR (M12)	0.44	RCP8.5	−2.28	−0.44	+0.94	+0.54	+36
RCA4 / MIROC5 (M14)	0.44	RCP8.5	+0.79	−5.39	−4.68	+0.71	−4
RCA4 / MPI-ESM-LR (M22)	0.44	RCP8.5	+0.74	−1.94	−1.61	+0.67	+24
RCA4 / NorESM1-M (M24)	0.44	RCP8.5	+0.03	−1.79	−0.41	+0.82	+47
REMO2009 / EC-EARTH (M8)	0.44	RCP8.5	+1.80	−1.25	−4.84	+0.80	−9
REMO2009 / HadGEM2-ES (M16)	0.44	RCP8.5	+0.53	−0.71	−3.02	+1.11	+23
REMO2009 / IPSL-CM5A-LR (M11)	0.44	RCP8.5	+2.51	−1.71	−5.69	+1.39	−4
REMO2009 / MIROC5 (M13)	0.44	RCP8.5	+1.94	−1.87	−5.15	+1.01	−4
REMO2009 / MPI-ESM-LR (M21)	0.44	RCP8.5	−0.52	−1.22	−2.13	+0.82	+17
CCLM4-8-17 / CNRM-CM5 (M3)	0.44	RCP4.5	−0.24	+0.68	+0.06	−0.01	−0
CCLM4-8-17 / EC-EARTH (M6)	0.44	RCP4.5	−0.58	+1.43	+0.86	+0.16	+20
CCLM4-8-17 / HadGEM2-ES (M15)	0.44	RCP4.5	+0.76	+2.40	+1.56	+0.21	+28
CCLM4-8-17 / MPI-ESM-LR (M19)	0.44	RCP4.5	+1.84	+0.07	−4.45	−0.10	−49
CRCM5 / CanESM2 (M1)	0.44	RCP4.5	−3.17	−0.48	+1.36	+0.36	+29
CRCM5 / MPI-ESM-LR (M20)	0.44	RCP4.5	+0.70	−0.96	−2.32	+0.38	+2
HIRHAM5 / EC-EARTH (M7)	0.44	RCP4.5	+1.13	−0.89	−2.86	+0.33	−9
RACMO22T / EC-EARTH (M9)	0.44	RCP4.5	+0.08	+0.97	+0.25	−0.14	−8
RACMO22T / HadGEM2-ES (M17)	0.44	RCP4.5	+0.58	+0.75	−1.04	−0.02	−9
RCA4 / CNRM-CM5 (M4)	0.44	RCP4.5	+1.14	−2.40	−1.63	+0.06	−9
RCA4 / CSIRO-Mk3-6-0 (M5)	0.44	RCP4.5	+0.49	−1.12	−1.66	+0.47	+7
RCA4 / CanESM2 (M2)	0.44	RCP4.5	+0.77	−1.57	−1.01	+0.47	+11
RCA4 / EC-EARTH (M10)	0.44	RCP4.5	−0.50	−0.36	+0.55	+0.46	+34
RCA4 / GFDL-ESM2M (M26)	0.44	RCP4.5	+0.13	−1.43	−0.91	+0.47	+20
RCA4 / HadGEM2-ES (M18)	0.44	RCP4.5	+0.99	−1.03	−0.74	+0.63	+27

Run	Grid (°)	Scenario	CDD	CWD	RR1	SDII	PRCPTOT
RCA4 / IPSL-CM5A-MR (M12)	0.44	RCP4.5	−1.02	−0.58	+0.68	+0.56	+29
RCA4 / MIROC5 (M14)	0.44	RCP4.5	+0.96	−4.77	−3.68	+0.44	−10
RCA4 / MPI-ESM-LR (M22)	0.44	RCP4.5	+1.45	−0.96	−2.94	+0.51	+0
RCA4 / NorESM1-M (M24)	0.44	RCP4.5	−1.20	−2.80	−0.61	+0.44	+22
REMO2009 / EC-EARTH (M8)	0.44	RCP4.5	−0.24	−1.12	−1.93	+0.56	+10
REMO2009 / MPI-ESM-LR (M21)	0.44	RCP4.5	+0.22	−1.31	−3.74	+1.08	+9
CCLM5-0-15 / HadGEM2-ES	0.22	RCP8.5	+1.00	−0.24	−0.45	+0.10	+0
CCLM5-0-15 / MPI-ESM-LR	0.22	RCP8.5	−1.38	−1.62	−0.96	−0.04	−12
CCLM5-0-15 / NorESM1-M	0.22	RCP8.5	+3.06	−2.35	−5.37	−0.22	−62
CanRCM4 / CanESM2	0.22	RCP8.5	−1.64	−0.20	+1.21	+0.96	+76
REMO2015 / HadGEM2-ES	0.22	RCP8.5	+0.63	−1.19	−3.85	+1.58	+37
REMO2015 / MPI-ESM-LR	0.22	RCP8.5	−0.01	−0.78	−2.26	+1.20	+38
REMO2015 / NorESM1-M	0.22	RCP8.5	+2.41	−1.12	−4.32	+0.65	−11
RegCM4-7 / HadGEM2-ES	0.22	RCP8.5	+0.44	−0.86	−0.50	+0.39	+22
RegCM4-7 / MPI-ESM-MR	0.22	RCP8.5	+1.92	−3.44	−4.96	−0.07	−58
RegCM4-7 / NorESM1-M	0.22	RCP8.5	+1.39	−2.78	−2.42	+0.21	−15
CanRCM4 / CanESM2	0.22	RCP4.5	−0.26	−1.61	−0.21	+0.84	+52

S4 Table (CDD). Provincial change, median and agreement. Effective cells as in Table 3.

Province	Cells	OND RCP4.5	OND RCP8.5	JFM RCP4.5	JFM RCP8.5				
Central	40.9	+1.79	81%	+2.73	91%	−0.17	52%	+0.28	64%
Copperbelt	13.4	+1.46	86%	+2.17	95%	−0.23	57%	+0.89	59%
Eastern	29.7	+1.82	81%	+2.90	91%	+0.34	67%	+0.64	73%
Luapula	21.3	+1.37	86%	+1.72	77%	+0.58	62%	+0.46	68%
Lusaka	9.6	+1.86	86%	+2.93	91%	+0.17	52%	+0.21	64%
Muchinga	29.6	+1.59	81%	+2.89	82%	+0.42	62%	+0.49	64%
North-Western	53.9	+1.17	86%	+1.76	100%	+0.08	62%	+0.39	68%
Northern	33.0	+1.54	76%	+1.86	77%	+0.33	67%	+0.21	68%
Southern	37.3	+2.16	90%	+2.36	95%	+0.62	62%	+0.68	64%
Western	55.5	+1.64	81%	+1.83	95%	+0.20	57%	+0.39	64%
Zambia	324.1	+1.65	95%	+2.23	95%	+0.49	67%	+0.51	68%

S4 Table (CWD). Provincial change, median and agreement. Effective cells as in Table 3.

Province	Cells	OND RCP4.5	OND RCP8.5	JFM RCP4.5	JFM RCP8.5				
Central	40.9	−0.60	67%	−0.55	68%	−0.16	57%	−0.63	64%
Copperbelt	13.4	−0.52	76%	−0.82	68%	−1.11	62%	−0.93	68%
Eastern	29.7	−0.48	81%	−0.75	77%	−0.76	86%	−0.88	73%
Luapula	21.3	−0.93	86%	−0.90	73%	−1.58	71%	−1.91	77%
Lusaka	9.6	−0.59	81%	−0.45	73%	+0.23	57%	−0.50	59%
Muchinga	29.6	−0.53	86%	−0.96	91%	−2.34	81%	−1.43	82%
North-Western	53.9	−0.68	67%	−0.85	77%	−0.49	67%	−0.91	64%
Northern	33.0	−0.87	76%	−1.24	91%	−2.01	71%	−2.24	77%
Southern	37.3	−0.53	71%	−0.67	73%	+0.21	62%	−0.47	68%
Western	55.5	−0.31	71%	−0.63	68%	+0.04	57%	−0.46	64%
Zambia	324.1	−0.66	81%	−0.75	91%	−0.96	71%	−0.85	73%

S4 Table (RR1). Provincial change, median and agreement. Effective cells as in Table 3.

Province	Cells	OND RCP4.5	OND RCP8.5	JFM RCP4.5	JFM RCP8.5
Central	40.9	-1.76	86%	-2.58	100%
Copperbelt	13.4	-1.89	95%	-2.98	100%
Eastern	29.7	-1.18	81%	-2.48	86%
Luapula	21.3	-1.76	90%	-1.94	86%
Lusaka	9.6	-1.33	76%	-2.56	100%
Muchinga	29.6	-1.98	86%	-2.64	91%
North-Western	53.9	-2.29	90%	-2.93	95%
Northern	33.0	-1.97	86%	-1.87	91%
Southern	37.3	-1.71	90%	-2.78	100%
Western	55.5	-2.28	90%	-3.56	95%
Zambia	324.1	-2.03	90%	-2.67	100%

S4 Table (SDII). Provincial change, median and agreement. Effective cells as in Table 3.

Province	Cells	OND RCP4.5	OND RCP8.5	JFM RCP4.5	JFM RCP8.5
Central	40.9	+0.18	76%	+0.53	91%
Copperbelt	13.4	+0.38	81%	+0.63	91%
Eastern	29.7	+0.28	81%	+0.62	91%
Luapula	21.3	+0.56	86%	+0.63	86%
Lusaka	9.6	+0.11	57%	+0.26	64%
Muchinga	29.6	+0.46	86%	+0.75	91%
North-Western	53.9	+0.28	95%	+0.51	91%
Northern	33.0	+0.47	76%	+0.58	82%
Southern	37.3	+0.12	57%	+0.45	73%
Western	55.5	+0.24	81%	+0.36	86%
Zambia	324.1	+0.31	90%	+0.60	86%

S4 Table (PRCPTOT). Provincial change, median and agreement. Effective cells as in Table 3.

Province	Cells	OND RCP4.5	OND RCP8.5	JFM RCP4.5	JFM RCP8.5
Central	40.9	-12	62%	-6	68%
Copperbelt	13.4	-3	57%	-3	64%
Eastern	29.7	-8	52%	-7	64%
Luapula	21.3	+6	57%	+3	55%
Lusaka	9.6	-14	76%	-20	73%
Muchinga	29.6	-10	52%	-6	59%
North-Western	53.9	-6	57%	-3	59%
Northern	33.0	+6	67%	+3	50%
Southern	37.3	-11	71%	-13	77%
Western	55.5	-13	71%	-6	77%
Zambia	324.1	-6	67%	-3	64%