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Large rainfall changes consistently projected over substantial areas of tropical land

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Many tropical countries are exceptionally vulnerable to changes in rainfall patterns, with floods or droughts often severely affecting human life and health, food and water supplies, ecosystems and infrastructure[1]. There is widespread disagreement among climate model projections of how and where rainfall will change over tropical land at the regional scales relevant to impacts[2-4], with different models predicting the position of current tropical wet and dry regions to shift in different ways[5,6]. Here we show that despite uncertainty in the location of future rainfall shifts, climate models consistently project that large rainfall changes will occur for a considerable proportion of tropical land over the twenty-first century. The area of semi-arid land affected by large changes under a higher emissions scenario is likely to be greater than during even the most extreme regional wet or dry periods of the twentieth century, such as the Sahel drought of the late 1960s to 1990s. Substantial changes are projected to occur by mid-century—earlier than previously expected[2,7]—and to intensify in line with global temperature rise. Therefore, current climate projections contain quantitative, decision-relevant information on future regional rainfall changes, particularly with regard to climate change mitigation policy.

Climate change is expected to drive changes in tropical rainfall by affecting both atmospheric moisture and circulation[8-11]. In the absence of circulation change, the enhanced capacity of warmer air to contain moisture would lead to increased $P-E$ (precipitation minus evaporation) in already wet regions and decreases in dry regions; the so-called 'wet-get-wetter, dry-get-drier' hypothesis[8,9,11]. This mode of change is present in both climate model simulations[9,11-13] and observed trends[13,14], and hence is an important validation of model fidelity, but is seen only when very large area averages are used[5,6]. At the regional scales more relevant to climate change impacts, the wet-get-wetter, dry-get-drier paradigm is not a good predictor of rainfall change in projections[5,6,15] or observations[16,17], and projections of future regional rainfall change vary widely across climate models[2,3,18,19].

Instead, the dominant driver of regional rainfall change in the tropics is the occurrence of shifts in the position of wet regions[5,6]. These spatial shifts can cause both increases and decreases in rainfall, and are illustrated here with two very different climate model projections of future precipitation (Fig. 1a,b). Large shifts occur in both models, and in each model are generally coherent in sign over areas large enough to affect whole countries or regions, but the locations of shifts differ greatly between the two. Uncertainty over which regions will experience these shifts, and to what extent, is the main cause of spread in regional rainfall projections[5,6], with even the sign of change uncertain in some regions[2,3]. This uncertainty impedes planning for adaptation to climate change. For global

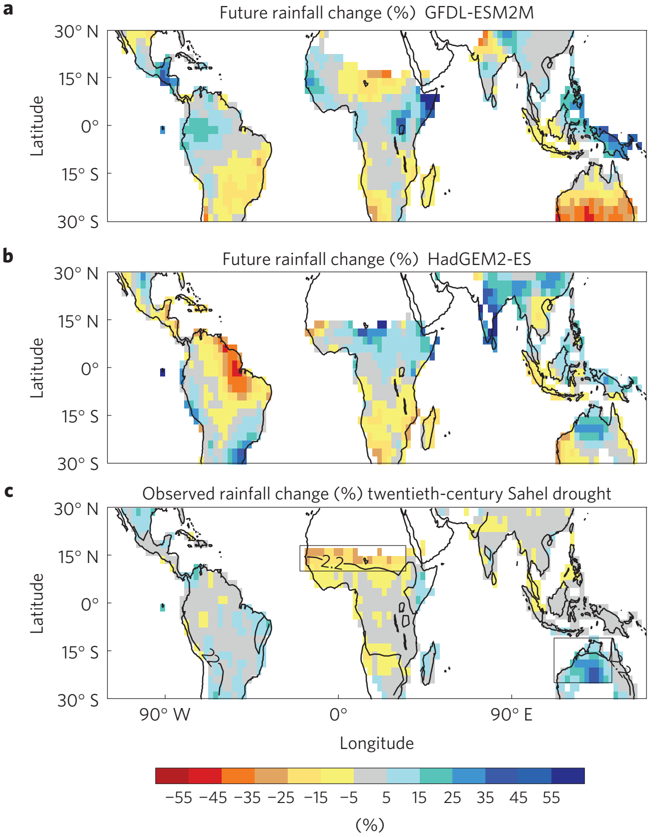

Figure 1 | Tropical land precipitation changes in two climate models, and observations of Sahel drought. a,**b**, Precipitation change for 2071–2100 minus 1971–2000, under the RCP8.5 emissions scenario for GFDL-ESM2M (**a**) and HadGEM2-ES (**b**). **c**, CRU observed rainfall change (%) for 1968–1997 minus 1938–1967. Desert and sea regions are masked in white. Outlined areas in **c** indicate Sahel and northwest Australia regions, and the black line contour indicates the upper rainfall threshold for semi-arid regions (2.2 mm d^{-1}).

climate change mitigation policy, however, the precise location of large rainfall changes may be less important than whether or not they will occur, combined with an estimate of their magnitude and areal coverage.

There are good physical reasons to expect rainfall shifts to occur (see later for a discussion of this), even though their position and magnitude are less certain. This implies that there may be useful information contained within future rainfall projections, which is lost by the commonly used approaches of either taking the ensemble

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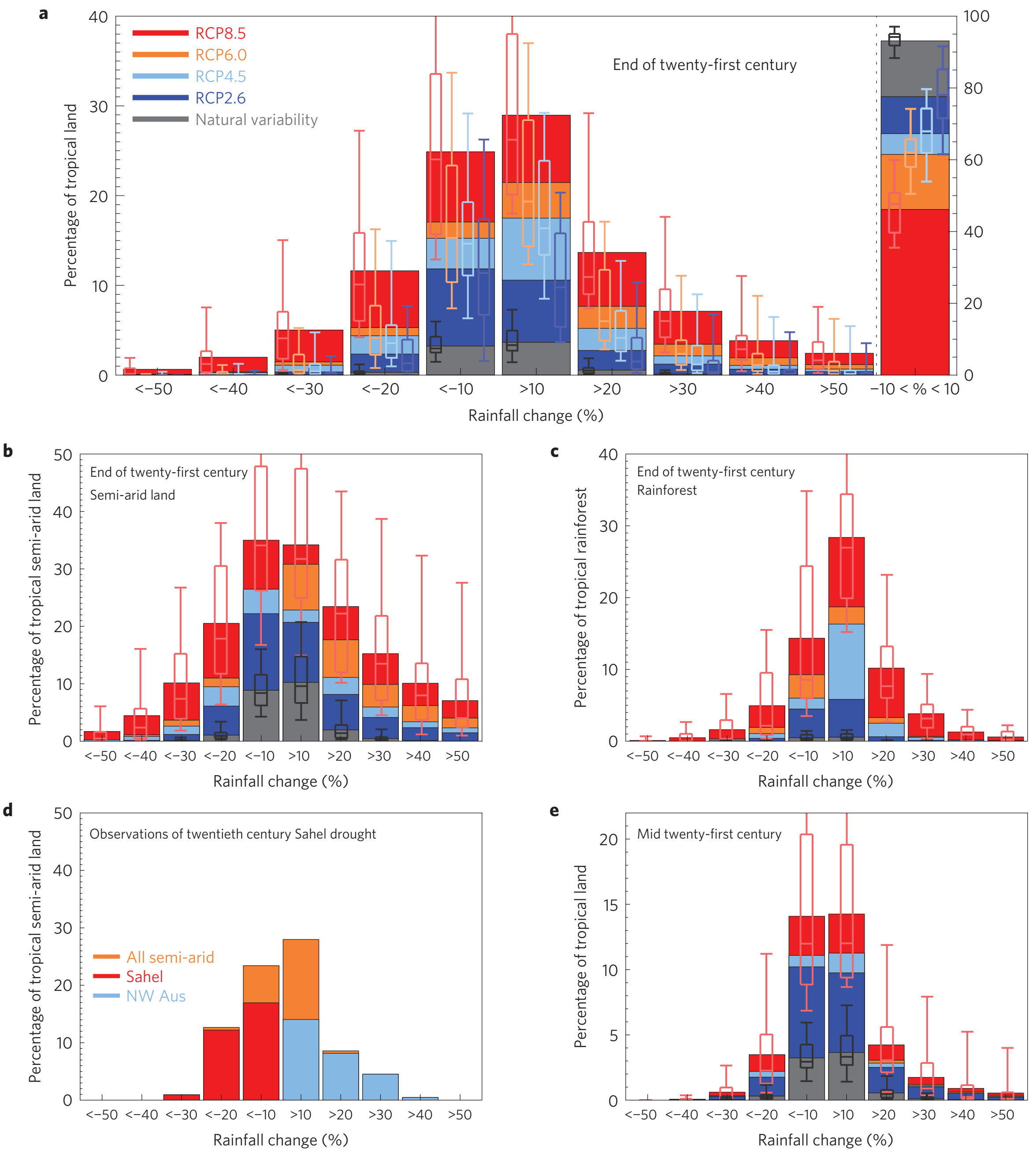

Figure 2 | Tropical land precipitation change. a–d, Bar charts showing the mean (across CMIP5 models) area of tropical land with precipitation changes at a number of thresholds. Four emissions scenarios and an estimate of natural variability are shown. Box–whisker plots indicate the median, inter-quartile range and 9th, 91st percentiles of the model spread for each scenario (**a**), or only RCP8.5 and natural variability (**b**,**c**,**e**). **a**–**c** show 2071–2100 minus 1971–2000, **b** shows tropical semi-arid regions, and **c** shows tropical rainforest regions. **d**, CRU observations over tropical semi-arid land for 1968–1997 minus 1938–1967. **e** shows mid-century projections, 2031–2060 minus 1971–2000. In **a** the −10<%<10 bin uses a separate *y* axis (right-hand side).

mean pattern of change across models, or analysing the spread of model projections on a region-by-region basis. Previous work has provided evidence of this by showing that when tropical regions (both land and sea) with future drying trends are determined on a model-by-model basis (without requiring different climate models to agree on the position of these regions), the magnitude of the mean drying trend across these regions is quite consistent across climate models[4]. Here, we consider whether models provide any consistent information about the magnitude and areal coverage of large, impact-relevant changes in rainfall across tropical land regions.

Therefore, we assess projections from 44 state-of-the-art CMIP5 (Coupled Model Intercomparison Project Phase 5) climate models by considering the total area of tropical land in each model where the magnitude of rainfall change exceeds a number of specified thresholds. That is, we examine the proportion of tropical land projected to undergo large rainfall changes in each model. Although the position of rainfall shifts varies across models, substantial changes are in fact present across all models and emissions scenarios (Fig. 2a).

By the end of the twenty-first century, large long-term rainfall changes (increases and decreases) of more than 20% are present across all models in RCP (Representative Concentration Pathway) 8.5 (Fig. 2a)—a higher emissions scenario with no explicit climate mitigation policy. Model estimates of the proportion of tropical land affected vary from 9.7% to 45.4%, with a mean of 25.3% (this analysis excludes desert areas—see Methods). Very large increases and decreases of more than 30% are present for greater than 90% of models, with mean area coverage of 12.1%. For comparison, Brazil, the largest tropical country, makes up about 13% of tropical land area, and a more average-sized country such as Kenya is around 1% of land area. The mean of model estimates for RCP8.5 suggests that more than half of all tropical land will experience substantial rainfall increases or decreases of greater than 10% (Fig. 2a).

Both large increases and reductions in regional rainfall are expected in semi-arid areas (Fig. 2b), which may be especially vulnerable to an increased likelihood of droughts or floods[1]—although rainfall increases could also bring positive impacts for some semi-arid regions. The proportion of semi-arid land with large changes is greater than for tropical land as a whole. Rainforest regions also show both increases and reductions (Fig. 2c), but the distribution is more skewed towards increases (although this is not true when only South America is considered—not shown).

To give context to our results, and to relate them to potential human impacts, we now examine perhaps the most severe long-term tropical drought of the twentieth century, the Sahel drought of the late 1960s to 1990s—which may itself have been at least partly anthropogenically forced by aerosol emissions[20]. Taking the 30 year mean observed change between the dry period of 1968–1997 and the preceding wet period of 1938–1967 (Figs 1c and 2d), the magnitude of drying was generally between 10% and 30% over semi-arid land in the Sahel. This is comparable to (or in fact smaller than) the magnitude of decreases consistently projected in semi-arid regions for 2071–2100 in RCP8.5 (Fig. 2b), and a larger area than during the Sahel drought is projected to be affected in the future by most models. Increased precipitation over semi-arid land in northwest Australia is also observed between these periods, again of similar or lesser magnitude and smaller land coverage than expected for end of twenty-first century RCP8.5 projections, and also perhaps linked to aerosol forcing[21].

Lower emissions scenarios have smaller rainfall changes than higher emissions scenarios—for the lowest emission scenario RCP2.6, between 0.4 and 15.5% of land experiences rainfall changes larger than 20%, with mean land coverage of 5.1% (Fig. 2a). However, substantial rainfall changes of greater than 10% are present even in RCP2.6, covering between 6.0% and 41.9% of land, with a mean coverage of 22.4%. The proportion of land projected to experience large regional rainfall change seems to be linearly related to change in global mean surface temperature (Fig. 3), which is itself linearly related to cumulative greenhouse gas emissions[2]. A similar linear relationship is found between global mean precipitation change and global mean temperature change[2], but it should be noted that the mechanisms are quite different—global mean precipitation change is governed by changes in the global mean energy balance[17,22], whereas regional changes are largely due to shifts in the position of wet and dry regions[5,6].

Changes larger than natural climate variability are already present in all emissions scenarios by mid-century (Fig. 2e), with RCP8.5 having rainfall increases and decreases of greater than 10% for all models, and greater than 20% for more than 90% of models. Model agreement on the occurrence of large regional rainfall change by mid-century is much sooner than suggested by previous work that estimated emergence time on a region-by-region basis[2,7], but is consistent with a previous estimate of emergence time for some precipitation 'hotspot' regions[23]. At mid-century, the differences between rainfall changes in the three lower emissions scenarios are relatively small (Fig. 2e).

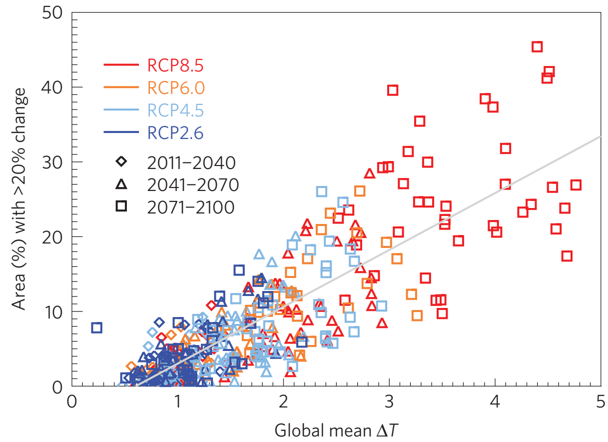

Figure 3 | Relationship between area of tropical land with large precipitation change and global mean temperature change. Area of tropical land with absolute precipitation changes (increases or decreases) of >20%, plotted against global mean surface temperature change for CMIP5 models in four emissions scenarios. Three time periods of 2011–2040 (diamonds), 2041–2070 (triangles), and 2071–2100 (squares) are shown, each with a baseline of 1971–2000. Grey line shows the linear least-squares fit to the data.

Although the position of rainfall shifts varies across models, the regions most likely to experience large rainfall increases and decreases can be identified by calculating the proportion of models that agree on a particular threshold of change (for example, >20%) at each grid point[4] (Fig. 4). Regions at greatest risk of large rainfall changes include southern and East Africa, Central America and India, although model agreement in each grid square is still only moderate even in these regions. In general, the regions with the greatest chance of large increases are distinct from those most likely to have large decreases. If a country is projected to be at risk from either a large increase or a large decrease, but not both, this may be useful for its adaptation planning—as the actions needed to prepare for large increases or decreases in rainfall are very different. However, there are a few regions (for example, parts of South and Central America and Australia) where both large increases and decreases are present across models. The regions where large changes are most likely (Fig. 4c,d) are generally consistent with the pattern of ensemble mean model rainfall change (Fig. 4a). Similarly, regions where the ensemble mean is small are the most likely to have no changes greater than 10% (Fig. 4b).

As climate models disagree on the location of rainfall shifts, should we trust the projection that such shifts will occur at all? Uncertainty in the pattern of shifts across models is likely to be due to a combination of two factors.

First, the number of processes with the potential to cause land rainfall shifts under global warming is large. The pattern of future sea surface temperature warming is crucial for rainfall pattern formation over the oceans[15], with rainfall tending to occur over the warmest regions, and this is also likely to influence rainfall over land. The enhanced land–sea temperature contrast in a warmer climate is expected to lead to rainfall shifts[24], with local land warming enhancing rainfall over land and remote sea surface temperature warming suppressing it[25]. A general increase in moisture transport may inherently drive dynamical feedbacks leading to shifts in wet and dry regions, the nature of which could be flow-dependent[8]. Rainfall in the margins of some convective regions may be reduced owing to the moisture flow into these regions not increasing sufficiently to meet the greater threshold for convection in a warmer atmosphere[8,11]. Reductions in near-surface relative humidity over some land regions could lead to rainfall shifts by affecting the

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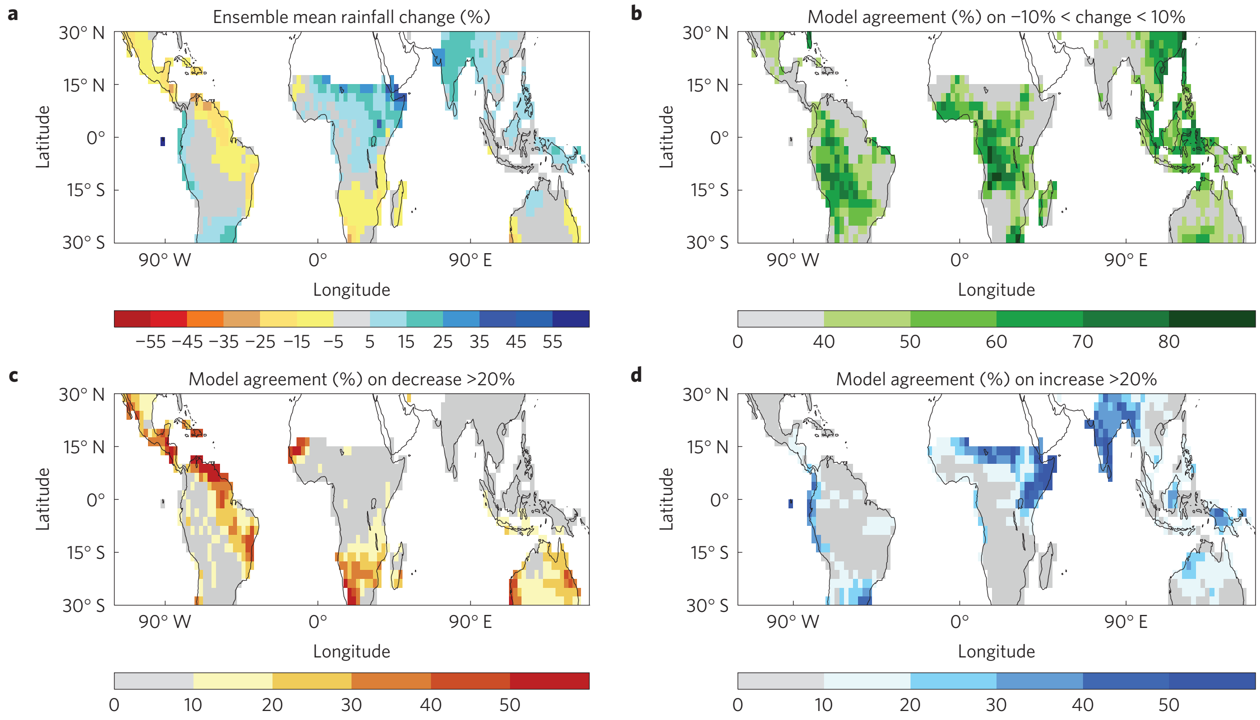

Figure 4 | Regions most likely to experience large precipitation changes. a, CMIP5 ensemble mean precipitation change, for 2071–2100 minus 1971–2000, under the RCP8.5 emissions scenario. Areas where 1971–2000 precipitation is <200 mm yr^{-1} are masked in white. **b–d**, Model agreement on precipitation changes at a number of thresholds, for 2071–2100 minus 1971–2000, under the RCP8.5 emissions scenario. Areas where <20 models have 1971–2000 precipitation of >200 mm yr^{-1} are masked in white.

height at which clouds can form[26]. The north–south position of wet regions in the tropics has been linked to the inter-hemispheric energy balance[27], and so any future change in this balance could lead to large-scale northward or southward rainfall shifts. One possible cause of such a change in energy balance is future changes in aerosol concentrations[28], which could also lead to more regional rainfall shifts[21]. Plant stomata also react directly to increases in CO_2 concentrations, reducing evapo-transpiration and potentially leading to feedbacks on the atmospheric circulation and rainfall[29]. Differences in the balance of these processes across models could lead to very different overall patterns of change.

Second, models are imperfect, with processes such as convection unable to be resolved at current grid resolutions and therefore parameterized, and they exhibit large present-day biases in their simulation of tropical rainfall (Supplementary Fig. 1). Biases vary between models, but common problems include a dry bias over parts of India, and a wet bias over much of southern Africa. The effect of climate change processes in a climate model may depend on the model's present-day biases[30].

Despite uncertainty about the location of rainfall shifts, there are good reasons to think that projections of the occurrence of shifts over tropical land are credible: rainfall shifts do occur in all models, and the locations of shifts in each model do not generally coincide with the locations of its biases (mean correlation coefficient of 0.24 for RCP8.5); several of the proposed mechanisms for future change[15,24,25] are also observed in present-day seasonal and inter-annual rainfall variability, and are reasonably well represented by models, for example, monsoon rainfall in response to increased land–sea temperature gradients, and land rainfall anomalies in response to sea-surface temperature change during El Niño events; model biases usually involve errors in the position or magnitude of rainfall regions, not their existence (Supplementary Fig. 1), and so may compromise only the position and magnitude of the response to forcing, not the existence of that response; tropical land rainfall shifts have been observed over the twentieth century[16], although only formally attributed to anthropogenic forcing in some cases[28]; large forced shifts in regional rainfall exist in the palaeoclimate record, with some of the same proposed mechanisms as for future change[31].

Reducing model uncertainty in regional climate projections remains a research priority. In particular, very high spatial resolution climate simulations may be necessary to better represent tropical rainfall processes, and so give greater confidence in future projections. However, our findings that climate models consistently project that large rainfall changes will occur over the twenty-first century for a considerable proportion of tropical land are likely to be relevant for a range of climate impacts studies as well as informing mitigation and adaptation policy.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

R.C. conceived the original idea for the study, and performed the analysis. All authors provided additional ideas, helped to refine the methodology, and contributed towards writing the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.C.

Competing financial interests

The authors declare no competing financial interests.

Methods

Data. CMIP5 climate model data (see List of Climate Models, below) for the four RCP scenarios (2006–2100), historical (1860–2005) and pre-industrial control experiments were regridded to a 2.5° grid. The domain was restricted to 30° N–30° S, and a sea mask applied. A sea mask from the HadGEM2-ES model was used, with areas with 100% sea fraction set to 0 and other areas set to 1. This was regridded to 2.5° resolution, and any areas with a regridded mask value of <0.5 were taken as sea points and masked for all models (see Fig. 1). This choice of mask retains a large number of coastal points in the data set, but the results of this study are not sensitive to this, and were very similar when a much stricter sea mask was applied as a test. This is because rainfall change over coastal grid points does not seem to behave in a systematically different way from inland grid points. Only one ensemble member was used for each RCP model run, although the effect of this was tested (see Estimation of internal climate variability, below).

CRU TS (Climate Research Unit Time Series) 3.21 observed rainfall data[32] were regridded to 2.5° and restricted to 30° N–30° S. For the calculation of biases shown in Supplementary Fig. 1, GPCP (Global Precipitation Climatology Project) version 2 data[33] were also used for comparison, but this made little difference and so is not shown. For the Sahel drought analysis the regions used were: Sahel (10° N–18° N, 20° W–35° E) and northwest Australian (25° S–11° S, 112° E–142° E)—see Fig. 1c.

As large percentage rainfall anomalies are commonly projected in desert regions, but correspond only to small absolute changes that are unlikely to have much impact in these largely uninhabited areas, a desert mask was used to remove these regions from the analysis, with a threshold of 200 mm yr^{-1} (0.55 mm d^{-1}). To identify semi-arid and rainforest regions, values of respectively 200–800 mm yr^{-1} (0.55–2.2 mm d^{-1}) and >1,640 mm yr^{-1} (4.5 mm d^{-1}) were used[34,35]. Results were found to be insensitive to the value of these thresholds (values of 100 mm yr^{-1} each side of each threshold were tested). Thresholds were applied to each model or observational data set based on their own rainfall climatologies, and the multi-model mean thresholds are shown in Supplementary Fig. 1. As a result of model biases, the semi-arid and rainforest rainfall regimes defined here for each model may not always be located in exactly the same regions as those in observations, but are nevertheless useful for indicating how rainfall changes in each model within each type of rainfall regime. An alternative method of applying thresholds based on the observed CRU climatology was also tested, and the results of this study were not found to be sensitive to this choice.

Annual mean totals were used instead of seasonal totals because annual mean percentage changes provide a more robust measure of large rainfall changes than seasonal percentage changes. The tropics-wide distribution of seasonal percentage change can be dominated by large dry-season percentage changes that correspond to only small absolute changes, and are unlikely to have major impacts. Seasonal changes can also correspond to changes in the timing of rainy seasons which, although important, do not necessarily mean that total rainfall amount has changed. Annual mean percentage changes are not affected by either of these issues.

Results are sensitive to the choice of grid-box size: models with higher-resolution native grids have greater percentage area coverage of large rainfall change when the data are analysed at this higher resolution, than after averaging to 2.5°. This is expected, as large rainfall changes are more common at higher spatial resolution owing to the smoothing effects of averaging. The choice of 2.5° used here seems to be sensible, as it is at the coarse end of CMIP5 simulations, and so allows them to be compared at the same scale without any unphysical regridding of coarse simulations to a higher resolution.

Estimation of internal climate variability. The distribution of rainfall changes expected between two 30 year means from internal climate variability was estimated using long climate model control runs under pre-industrial greenhouse gas forcing. Two hundred and forty years were used from each model control run, each containing 8 consecutive 30 year periods. Mean variability was estimated for each model by taking the difference between each pair of non-consecutive 30 year periods, separating the resulting anomaly grid points into rainfall threshold bins (for example, >10% increase) and then finally dividing the number in each bin by the number of pairs of time periods. Only non-consecutive periods were used in case consecutive periods were more highly correlated with one another than non-consecutive ones.

This method makes the assumption that 30 year mean internal rainfall variability remains the same under forcing. To test this, an alternative method was also used, where models with at least two ensemble members of RCP4.5 were used. In this case, natural variability for each model was estimated by taking the difference between 30 year means of the projected future rainfall change of the two ensemble members. The resulting distribution of model estimates was very similar to that obtained using control runs, although with slightly wider uncertainty ranges—probably due to only two ensemble members being used as compared with eight different time periods in the control run method . Therefore, we consider that the control run method of variability estimation is robust. The relatively low tropical rainfall variability found here on 30 year timescales is also consistent with a previous estimate[6].

Reliability of model estimates of multi-decadal variability. Multi-decadal internal climate variability has been estimated here from climate models. To try to assess how valid these model estimates are, 30 year CMIP5 variability over the twentieth century was compared with corresponding variability in observed CRU data across tropical land. This exercise is hindered by the fact that both anthropogenic and natural forcing are present in both reality and historical model runs, and so the comparison measures the response to forcing as well as the range of natural variability. Observational error may also be substantial, particularly in the early part of the century where observations in the tropics are sparse.

Three consecutive 30 year means (1916–1945, 1946–1975, 1976–2005) were used from both observations and historical model simulations. Combined forced and internal variability was estimated by taking the difference at each grid point between each pair of time periods, separating into threshold bins, and then dividing the number in each bin by the number of time-period pairs (Supplementary Fig. 2). CRU variability is outside (above) the range of model estimates for changes >10%, and just inside the range for changes >20%. It is unclear what proportion of this discrepancy is due to the response to forcing, natural variability or observational uncertainty.

If models do systematically underestimate either variability or the historical response to forcing, then this could also have implications for the reliability of their future response to forcing. One possibility is that some future 30 year mean rainfall changes could be larger than projected at present.

List of climate models. ACCESS1-0, ACCESS1-3, BCC-CSM1-1, BCC-CSM1-1-M, BNU-ESM, CanESM2, CCSM4, CESM1-BGC, CESM1-CAM5, CMCC-ESM, CMCC-CM, CMCC-CMS, CNRM-CM5, CSIRO-Mk3-6-0, EC-EARTH, FGOALS-G2, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H_p1, GISS-E2-H_p2, GISS-E2-H_p3, GISS-E2-H-CC, GISS-E2-R_p1, GISS-E2-R_p2, GISS-E2-R_p3, GISS-E2-R-CC, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-LR, MPI-ESM-MR, MPI-ESM-P, MRI-CGCM3, NorESM1-M, NorESM1-ME.

Of these 44 models, 39 had output for RCP8.5, 25 for RCP6.0, 42 for RCP4.5, and 32 for RCP2.6. Control run data were available for 39 of the models.

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