Possible futures for East Africa under a changing climate:

Technical appendix for HyCRISTAL's Climate Risk Narratives

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Three possible futures for rural and urban East Africa in 2050 have been described in the narratives and infographics produced by the FCFA (Future Climate for Africa) HyCRISTAL project (Integrating Hydro-Climate Science into Policy Decisions for Climate-Resilient Infrastructure and Livelihoods in East Africa, Marsham et al. 2015); see Burgin et al. (2019a,b; hereafter B19). These three futures are a deliberate simplification to plausible quasi-quantitative climate scenarios as compared to the full complexity found by analysing around 40 projections from all available differing climate models alongside other sources of information. This approach has been inspired by the conceptual thinking of Jack et al. (2019) which has parallels with the work on narrative and storyline approaches in Dessai et al. (2018). The three climate futures used in the HyCRISTAL narratives do not therefore cover every possible outcome, but instead quasi-quantitatively illustrate the range of uncertainty inferred from climate projections for the coming decades. The three HyCRISTAL futures have been given these summary headlines:

Future 1: Much wetter, large increase in extreme rainfall and hotter

Future 2: Increase in extreme rainfall and hotter

Future 3: Much hotter and drier with more erratic rainy seasons

This appendix summarises the underlying climate information and science upon which the climate content of these three futures has been determined. These characteristics were deduced by expert judgement and discussion between climate scientists working on the HyCRISTAL project. Their aim was to select characteristics that span a range (but not necessarily the largest extremes) across the model outputs to highlight the areas of risk and uncertainty. They also ensured physical consistency between the indices used to describe the climate in each version of the future. The detailed information discussed by the climate scientists was then reduced to: (a) the broad summary phrases above, and (b) the short story format of B19's 'Briefs', which have an emphasis on non-technical language and are written as if in the present-day. Summary bar graphs were also produced to accompany the stories using values from the climate model projections. This climate information was then combined with impacts assessments to formulate the infographics and briefs.

Two types of climate model data were employed. First, a selection (detailed below) was taken from the multiple global climate models available from phase 5 of the Coupled Model Intercomparison

Project (CMIP5; Taylor et al. 2012). We focus on future projections for the period 2040-2060, forced by the high emissions 'representative concentration pathway 8.5' (RCP8.5). Anomalies are computed from historical simulations that use realistic anthropogenic and natural forcings, averaging over the period 1980-2010. Although different global models have differing performance for current climate, there is no simple mapping from this to their expected reliability for climate change, so we accept all predicted futures as plausible, unless research has shown otherwise (noting that Rowell 2019 shows March-April-May rain change in IPSL-CM5A is implausible). Second, we also analyse data from a convection-permitting version of the Met Office Unified Model run over a pan-African domain on a 4.5km grid (hereafter CP4A). An historical simulation (Stratton et al. 2018) for 1997-2008 is forced by the observed atmospheric composition and sea surface temperatures (SSTs), and at its lateral boundaries by a similarly forced global atmosphere-only simulation. A 10-year future simulation (Kendon et al. 2019) is forced by RCP8.5 greenhouse gas concentrations, SST anomalies from the CMIP5 HadGEM2-ES projection, and lateral boundary data from a similarly forced global atmosphere-only projection, all representative of circa 2100. This model is known to have an improved representation of intense rainfall events when compared to a standard parameterised-convection model (Kendon et al. 2019, Finney et al. 2019).

We address each of the climate variables in turn, that together constitute the three climate narratives, first quoting the relevant content of B19's 'Briefs' and then describing the climate information on which this content was based.

Mean seasonal rainfall

Future 1: "In Future 1 in 2050, it is much wetter than it used to be a few decades ago. The total amount of rainfall in the Long Rains has increased by around 25% and the Short Rains are about 20% wetter on average."

Future 2: "In 2050 in Future 2, it is a bit wetter during the Long Rains than it used to be in previous decades, with seasonal totals having returned to the levels seen in the 1970s and 1980s. The Short Rains are much the same as they were at the start of the century."

Future 3: "The Long Rains have continued to decline, and seasonal totals are about 5% less than they used to be compared with the start of the century. The Short Rains are around 7% drier than in previous decades."

These future rainfall scenarios were determined by examining the change in mean rainfall over the Lake Victoria Basin (LVB) region across 31 CMIP5 models in the March-April-May Long Rains season (Figure 1) and the October-November-December Short Rains season (Figure 2) and converted to percent data. Temporal variations in the data were also assessed using previously published literature including Rowell et al. (2105). Three models were chosen to represent plausible changes in future rainfall across the uncertainty space, but not necessarily representing any extreme case; CanESM2 for Future 1, BCC-CSM1.1 for Future 2 and HadGEM2-ES for Future 3. Rowell (2019) does not rule any of these out as implausible. The LVB average seasonal changes in rainfall are shown in Figure 3.

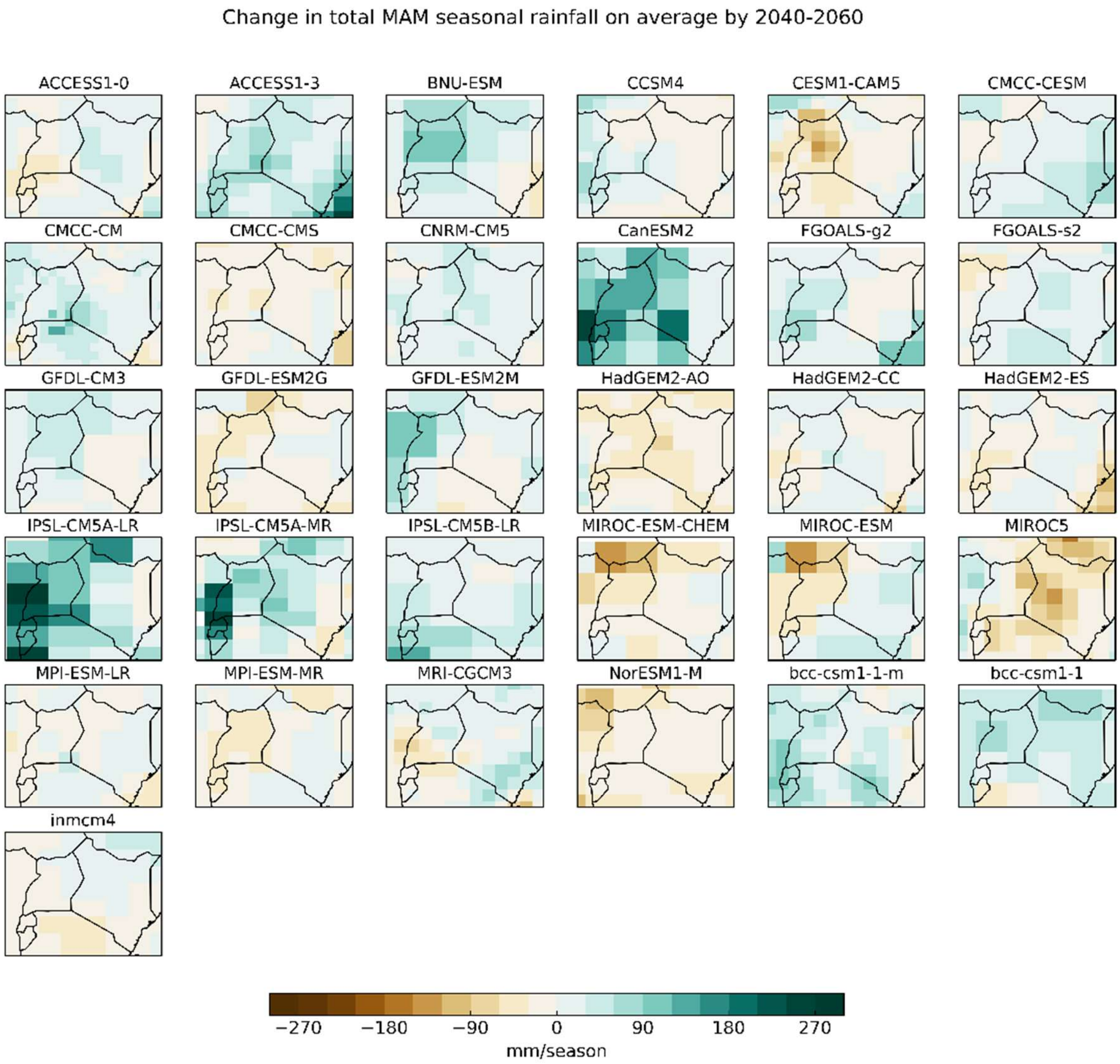

Figure 1: Change in total March-April-May (MAM) seasonal rainfall on average in 2040-2060 from a baseline of 1980-2010 for 31 CMIP5 GCMs under RCP8.5.

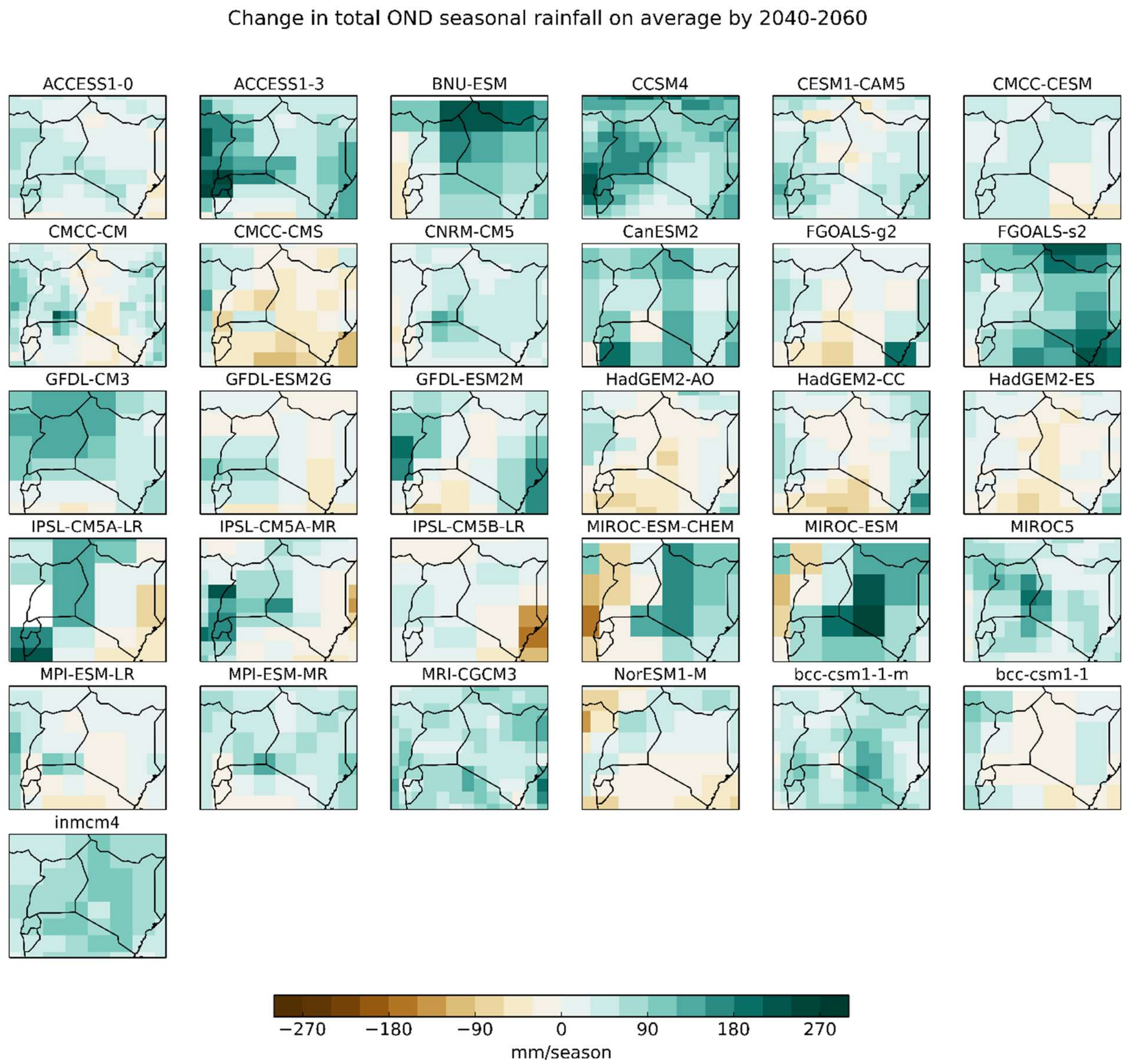

Figure 2: Change in total October-November-December (OND) seasonal rainfall on average in 2040-2060 from a baseline of 1980-2010 for 31 CMIP5 GCMs under RCP8.5.

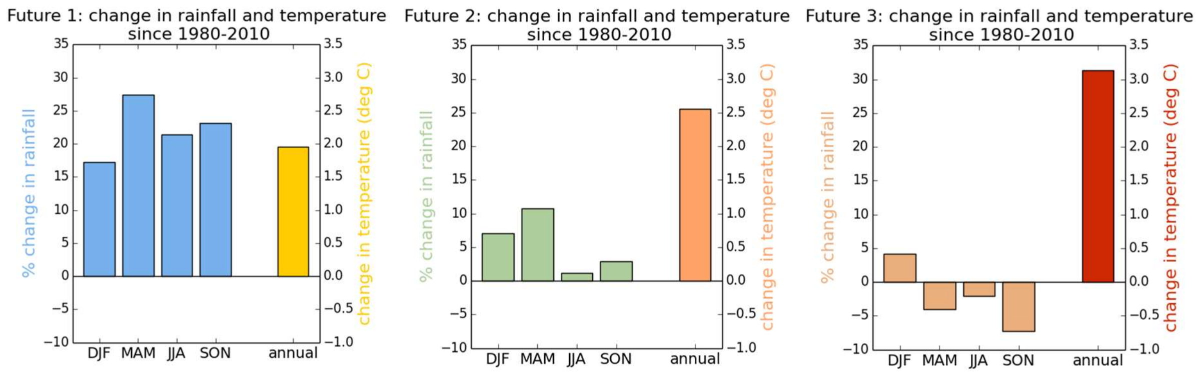

Figure 3: Change in seasonal mean rainfall (4 left-hand bars) and temperature (right-hand bar) in 2040-2060 from 1980-2010, from different CMIP models using RCP8.5, selected to represent the three different futures. From Burgin et al. (2019a,b).

Heavy rainfall

Future 1: "When it rains, it is usually much more intense and severe storms occur around five times more frequently."

Future 2: "However, when it rains it is often much heavier than it used to be, and extreme storms occur about two or three times more frequently."

Future 3: "When it does rain, showers are sometimes much heavier than they used to be."

These statements were largely derived from results from the ground-breaking CP4A model produced by the FCFA IMPALA project (Kendon et al 2019). This paper concludes that changes in extreme rainfall and dry spells over Africa may be underestimated in all models where convection is parameterised, i.e. all CMIP (Taylor et al 2012) & CORDEX (Endris et al 2013) models. For extreme rainfall, results from lower resolution modelling from CMIP5 GCMs were therefore not included as evidence in this section.

Kendon et al. (2019) show that for Africa as a whole, during the wet season (defined as the 3 month period with the highest rainfall for each grid-point), exceedance of the present-day 99.9th-percentile occurs almost three times more frequently at the end of the century in CP4A compared with the present-day. For East Africa, the 99.9th-percentile is equivalent to exceeding 60mm accumulation over 3 hours, and for this region is 7-8 times more frequent at the end of the century compared with the present day. This was scaled to the middle of the century (the time period of the narratives) using expert judgement to be around five times more frequent for a high-end scenario such as Future 1. Future 2 was estimated to have a mid-range increase in extremes. Future 3 was based on results from Kendon et al. (2019) and physical understanding that some (unquantified) increase in the frequency of intense rainfall events is likely even in areas with reduced mean annual rainfall under climate change.

Temperature

Future 1: "It is hotter in 2050, with average annual temperatures about 2°C higher than at the start of the century. Maximum temperatures have also risen, making the hottest days feel much hotter, particularly in cities."

Future 2: "Average annual temperatures have increased by 2-3°C and even higher temperature rises are felt in urban areas. Maximum temperatures have also increased by a similar amount and hot days are now extremely hot."

Future 3: "Temperatures have risen substantially by 2050 in Future 3. These are on average about 3°C hotter across the region. Maximum temperatures have also increased so the hottest days of the year are now unbearably hot, especially in urban areas."

Changes in annual mean all-day and daily maximum temperatures were assessed using the CMIP5 ensemble displayed as maps for the LVB region (Figures 4 and 5) and as box and whisker plots (Figures 6 and 7, from Bornemann et al. 2019). Expert opinion was used to select temperature increases that made physical sense for the rainfall scenarios chosen, whilst ensuring they spanned a range across the ensemble of future change. The LVB average annual temperature changes are shown in Figure 3.

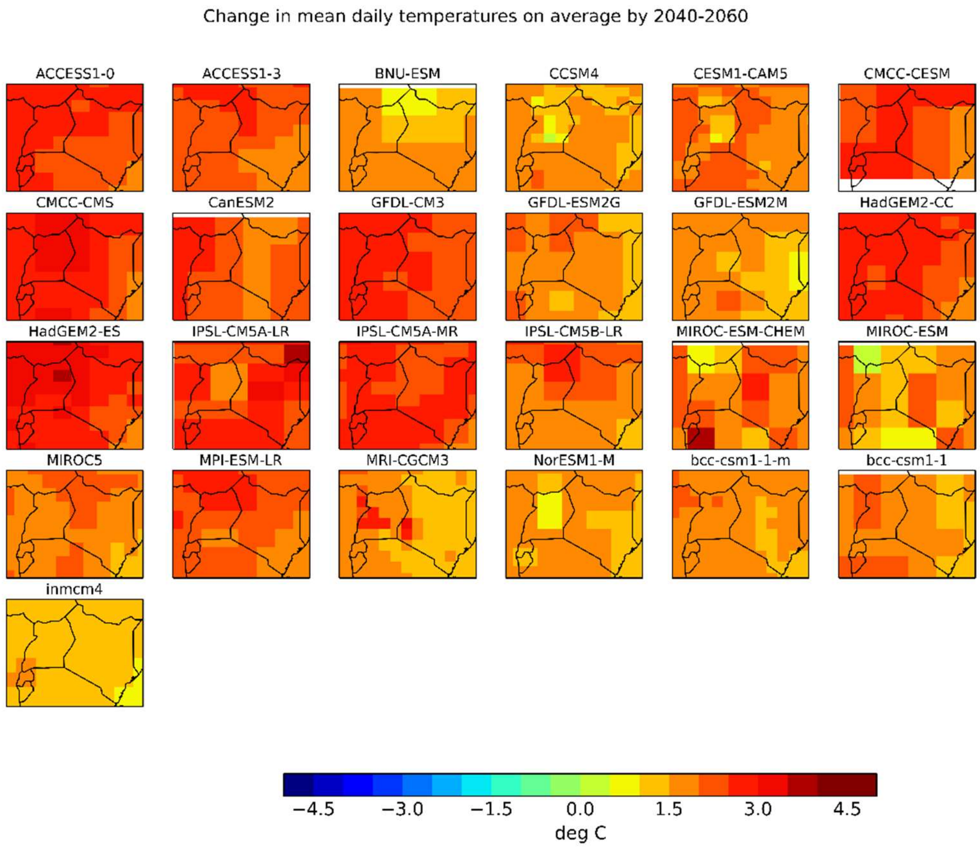

Figure 4: Change in annual mean daily temperature in 2040-2060 from a baseline of 1980-2010 for 31 CMIP5 GCMs under RCP8.5.

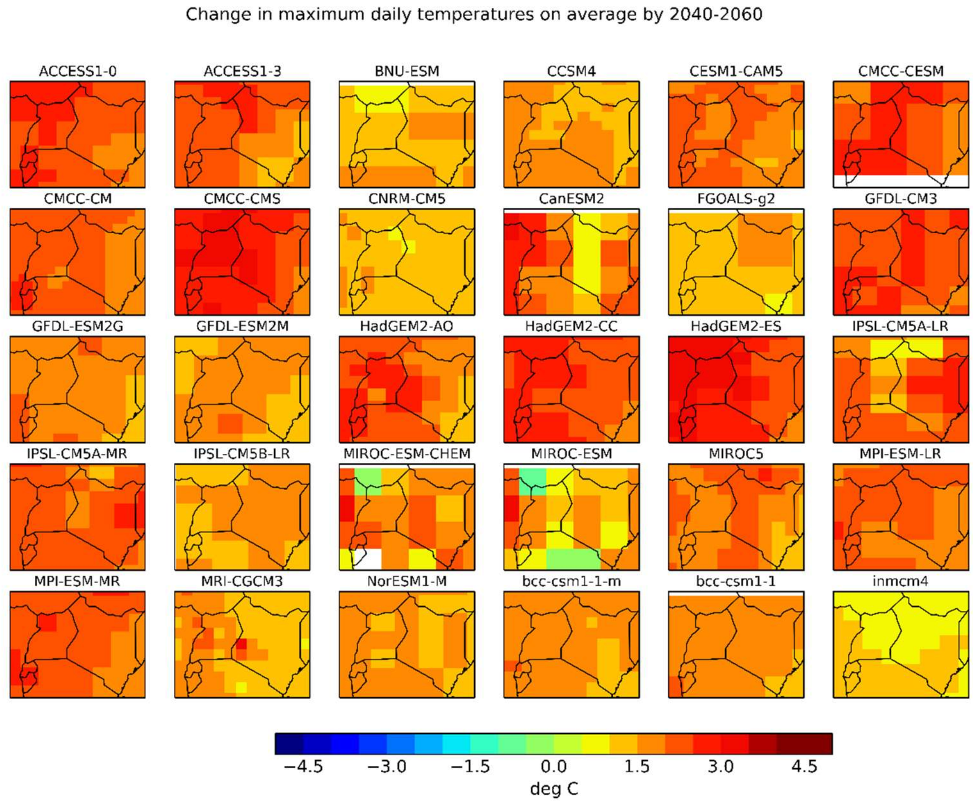

Figure 5: **Change in annual mean maximum daily temperature in 2040-2060 from a baseline of 1980-2010 for 30 CMIP5 GCMs under RCP8.5.**

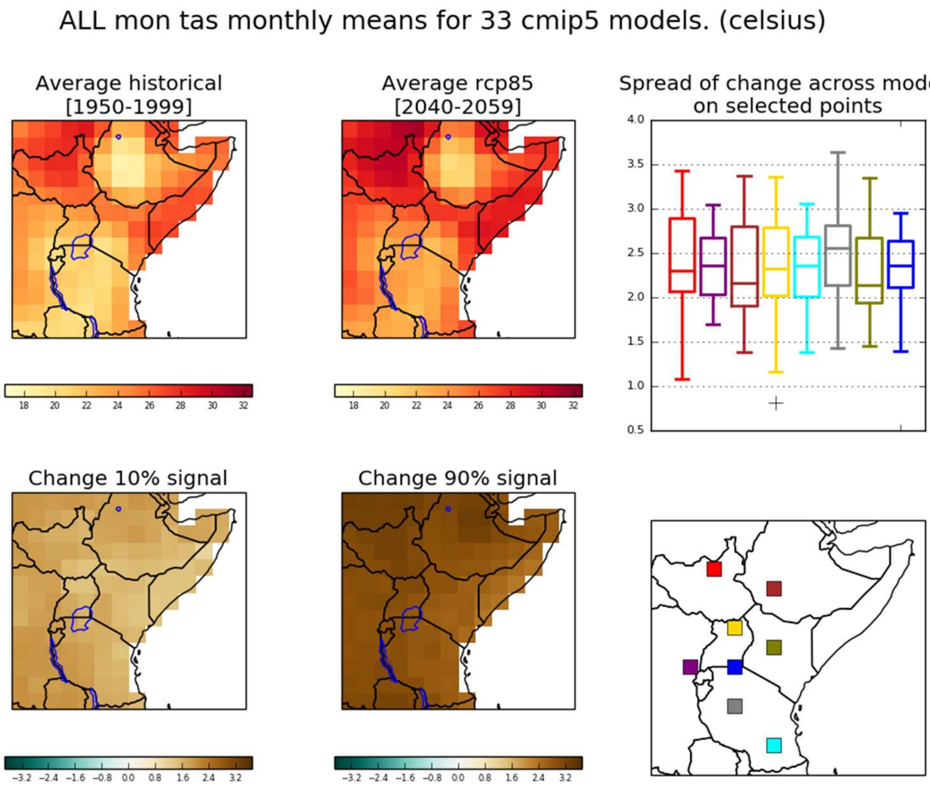

Figure 6: Annual mean of daily mean temperature across East Africa. Maps for the historical period (top left) and the future period under RCP8.5 (top centre). Maps of the 10th and 90th percentiles of the distribution of temperature change across different climate models (bottom left and bottom centre). Box-and-whisker plots of temperature change (top right) at 8 representative locations (bottom right). From Bornemann et al. (2019).

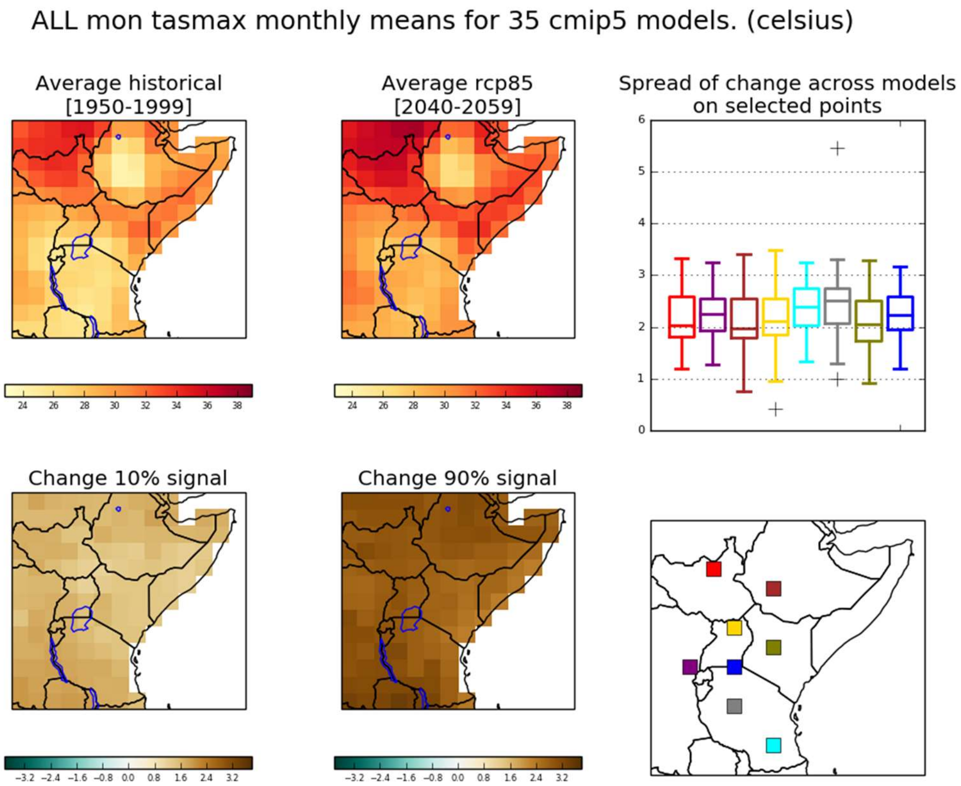

Figure 7: As Fig.6, but annual mean of daily maximum temperature. From Bornemann et al. (2019).

Seasonality of rainfall

Future 1: "The Short Rains now last longer by about a week and the Long Rains start several days earlier too."

Future 2: "Overall, the timings of the rainy seasons have not changed much, with their onset and cessation occurring at roughly the same time as they used to."

Future 3: "The Long Rains are about 10-15 days shorter than at the start of the century and the Short Rains have seen a reduction of at least 5 days."

Changes in rainfall seasonality in the region were assessed using results published by Dunning et al (2018). Daily precipitation data from 29 models used in CMIP5 were used to analyse onset and cessation dates (Figures 8 and 9). Future 1 was based on approximately the multi-model mean. As there is a large envelope of uncertainty around future seasonality of rainfall, Future 2 was used to represent the possibility that onset and cessation dates may not change very much by mid-century. Future 3 represents a more extreme case towards the edge of the distribution to show that shorter, but still plausible, rainfall seasons could occur.

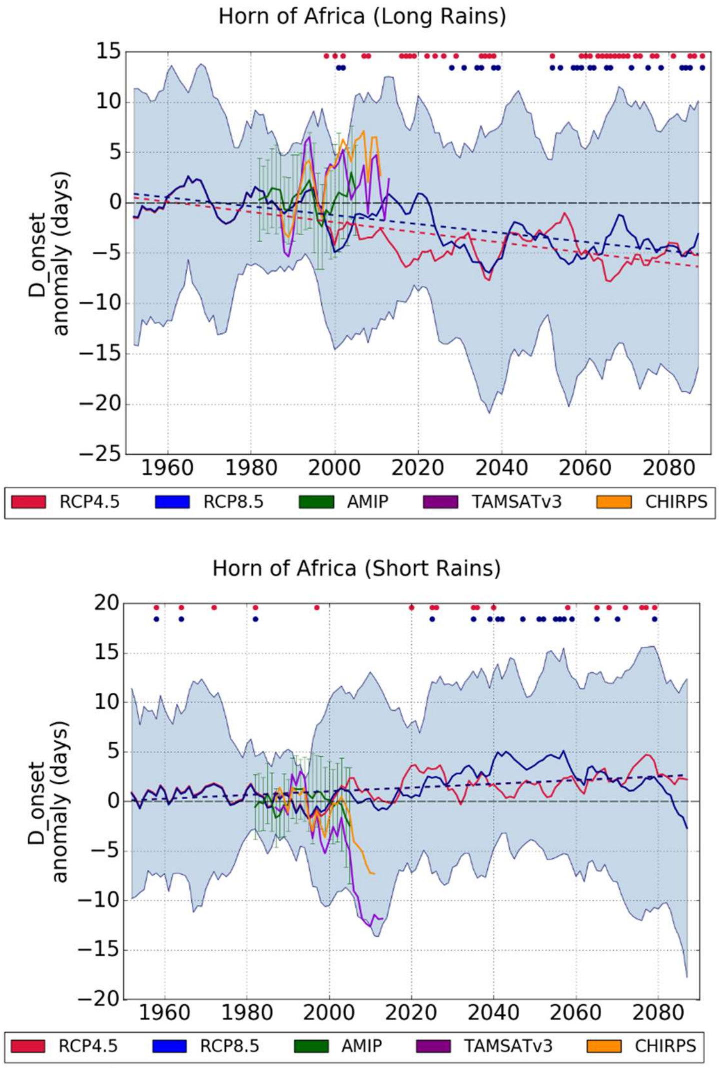

Figure 8: Time series of onset in the Long Rains and Short Rains over the Horn of Africa region. The red and blue lines are the multimodel mean (from 29 CMIP5 models) after a 5-yr running mean was applied for RCP4.5 and RCP8.5, respectively, over 1950–2090. The blue shaded area is plus and minus one standard deviation for the RCP8.5 simulation (the spread for RCP4.5 was similar). The green line (with error bars) is the multimodel mean (plus and minus one standard deviation) for AMIP simulations (1979–2008). The purple line is produced using TAMSATv3 precipitation (1985–2015). The dots indicate when the range of values from 29 models for that year is significantly different from the range for 1980–2000 at the 5% level, using a Mann–Whitney U and t test. From Dunning et al. (2018).

Cessation of rains

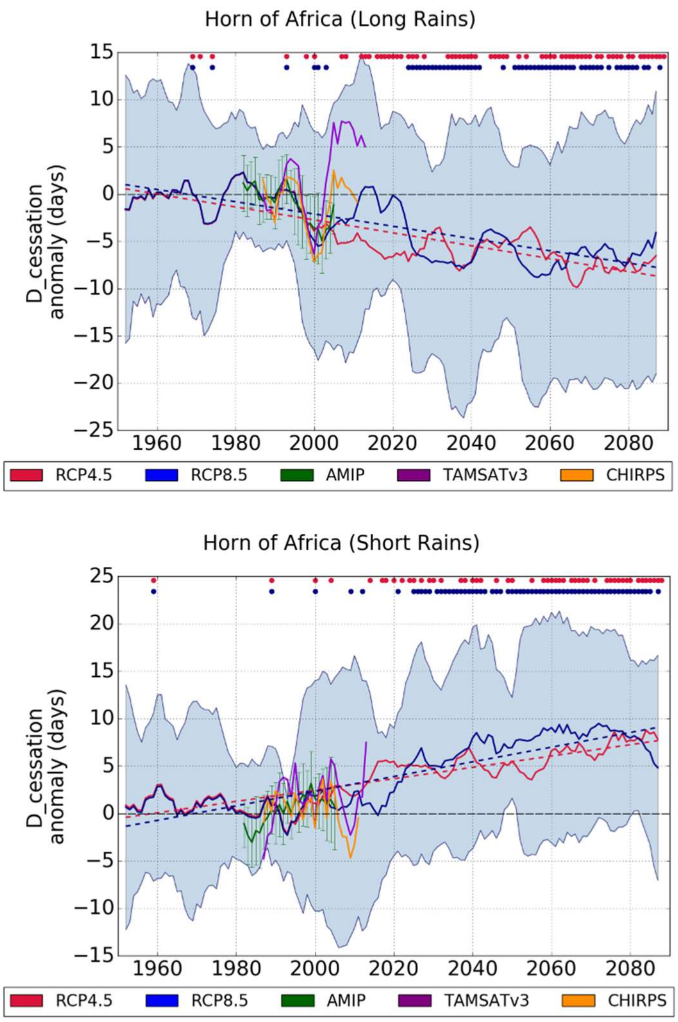

Figure 9: As Fig.8, but for cessation of the Long Rains and Short Rains. From Dunning et al. (2018).

Dry spells within rainy seasons

Future 1: "Dry spells still occur within the rainy seasons as they used to at the start of the century."

Future 2: "Dry spells are now about 50% longer than they used to be compared with the start of the century."

Future 3: "Dry spells are common within the rainy season and often last twice as long as they used to a few decades ago."

Information about changes in dry spell duration were also taken from the CP4A model as described in Kendon et al (2019) with figures reproduced for the LVB region (Figure 10). This model, and parallel simulations with a parameterised-convection model (R25), both show an increased probability of dry spell durations lasting around 2 to 6 days, and a slight decrease in the frequency of longer dry spells. Dry spells in the present-day period occur most frequently with durations under 5 days. The three future narratives were based around scenarios which become progressively more extreme away from the wet CP4A projection. Expert judgement for Future 1 is that increases in rainfall intensity could be the dominant cause of the increase in seasonal totals, with dry-spells echoing current natural variability., There may however be differential changes in the frequency of short versus long dry spells (Figure 10), but further model evaluation is required to better evaluate this facet of risk. Future 3 represents the upper end of the projection, with expert judgement suggesting a doubling of dry spell duration, and Future 2 is a mid-range scenario with a moderate increase in dry spell severity.

Lake Victoria levels

Future 1: "Lake Victoria levels have the potential to rise by at least a metre to those seen in the 1960s, depending on hydropower use. River levels have also markedly increased."

Future 2: "Lake Victoria has the potential to rise by about half a metre, depending on how much water is used for hydropower. River levels are also higher."

Future 3: "Lake Victoria levels have dropped by a metre. River levels in the region have also fallen."

Changes in lake-level values are based on the work of the 'HyCRISTAL Transport Pilot Project' (HyTpp), funded by UK Aid from the UK Department for International Development (DFID), through the Corridors for Growth Trust Fund, administered by the World Bank. A paper is in preparation. Lake Victoria is a unique hydro-meteorological system, with the main water source being on-lake rain (not river inflow) and the main loss being lake evaporation (not river outflow). HyTpp determined a plausible range in lake levels using projected changes in precipitation and evaporation from CMIP5 models, as well as CP4A and R25, to drive a lake water balance model. Lake outflow was assumed to be governed by the 'Agreed Curve', by which higher lake levels are partially managed via increased outflow, and *vice versa*. Future 1 was based on those CMIP models where increased rainfall most outweighed the increased evaporation. Future 2 is based on this narrative's smaller rainfall increase, giving a small lake-level rise. Future 3 is based on models where increased evaporation adds to a rainfall decrease.

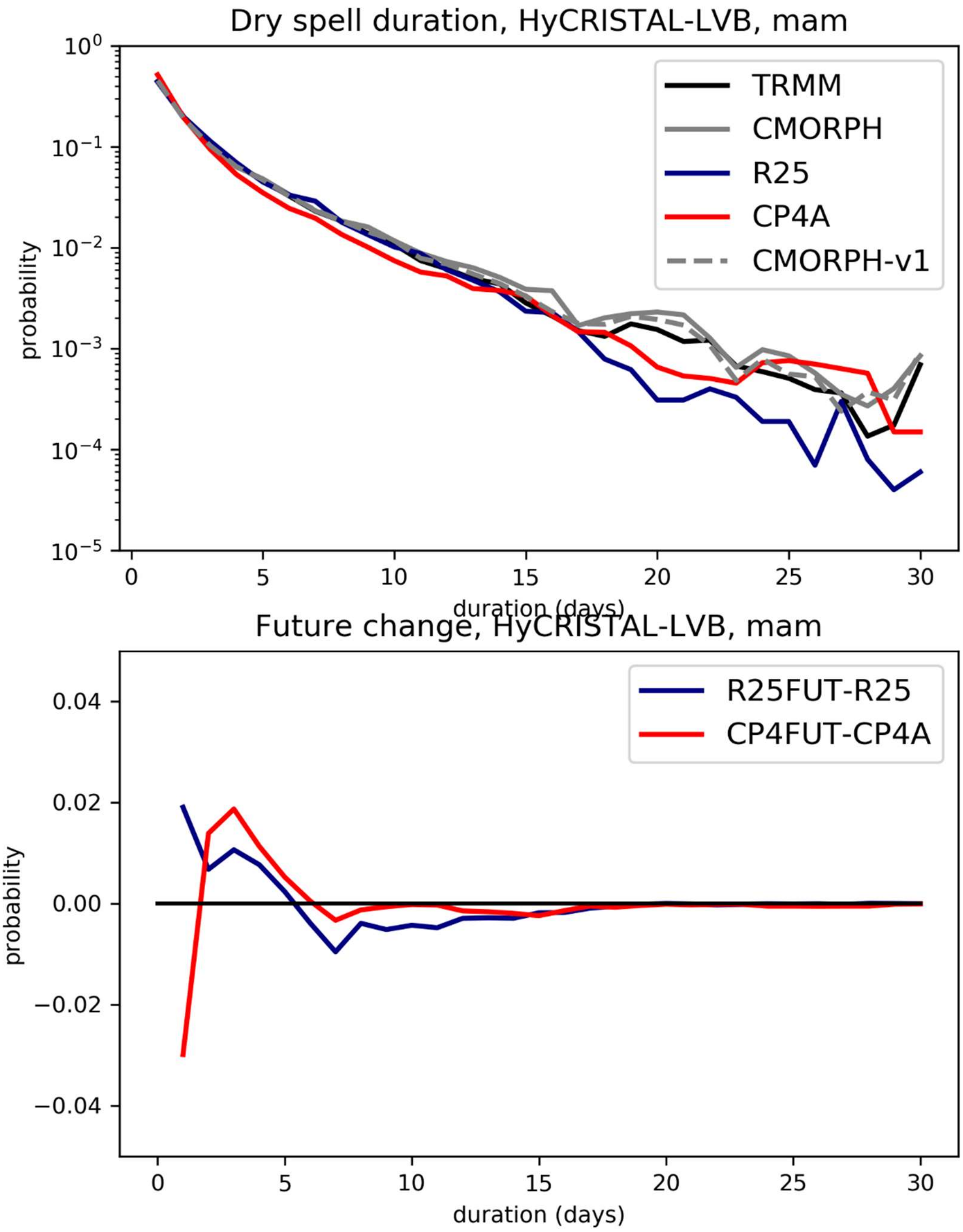

Figure 10: Dry spell duration probability for the present-day period (top panel) derived from the CP4A (red line) and R25 (blue) models and for TRMM (dark grey), CMORPH (light grey) and CMORPH-v1 (dashed grey) observation datasets. Future change in dry spell duration (bottom panel) for CP4A (red) and R25 (blue). From Kendon, E., personal communication, 2018.

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