BAMS Article

Convection-Permitting Regional Climate Change Simulations for Understanding Future Climate and Informing Decision-Making in Africa

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ABSTRACT: Pan-Africa convection-permitting regional climate model simulations have been performed to study the impact of high resolution and the explicit representation of atmospheric moist convection on the present and future climate of Africa. These unique simulations have allowed European and African climate scientists to understand the critical role that the representation of convection plays in the ability of a contemporary climate model to capture climate and climate change, including many impact-relevant aspects such as rainfall variability and extremes. There are significant improvements in not only the small-scale characteristics of rainfall such as its intensity and diurnal cycle, but also in the large-scale circulation. Similarly, effects of explicit convection affect not only projected changes in rainfall extremes, dry spells, and high winds, but also continental-scale circulation and regional rainfall accumulations. The physics underlying such differences are in many cases expected to be relevant to all models that use parameterized convection. In some cases physical understanding of small-scale change means that we can provide regional decision-makers with new scales of information across a range of sectors. We demonstrate the potential value of these simulations both as scientific tools to increase climate process understanding and, when used with other models, for direct user applications. We describe how these ground-breaking simulations have been achieved under the U.K. Government's Future Climate for Africa Programme. We anticipate a growing number of such simulations, which we advocate should become a routine component of climate projection, and encourage international coordination of such computationally and human-resource expensive simulations as effectively as possible.

KEYWORDS: Climate change; Climate prediction; Convective storms; Climate models; Model evaluation/performance

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There is an urgent need to provide actionable climate information for decision-makers in Africa to support planning for climate resilience and adaptation informing sustainable poverty alleviation strategies (Jones et al. 2015). Such information needs to be built on reliable projections of future climate from climate models.

The climate of Africa is diverse, ranging from the hyperarid Sahara to the semiarid savannas of the Sahel and the south, and the tropical forests in the center and west of the continent. These variations are further modulated by coasts and mountain ranges. Rainfall is dominated by the annual migration of the tropical rainband, again modulated by regional influences. This brings a single short rainy season at the northern extremity of the migration in the Sahel and a longer season over southern Africa at the southern extremity: between these there are generally two seasons associated broadly with the northward and southward passage of the tropical rainband (Dunning et al. 2016). Rainfall variability on all scales across these climates is high and contemporary climate models show only a modest ability to capture key driving processes with a slow rate of improvement (Flato et al. 2013), although higher-resolution regional simulations (~50 km) do show improvement in the spatial characteristics of extreme rainfall (Gibba et al. 2019). To support climate change adaptation in Africa, it is crucial to intensify efforts on improvement of the physical basis of climate models in their representation of processes crucial for Africa as well as in the immediate development of climate change information and advice using current best-available models and methods.

In recognition of these two imperatives and of the benefits of their integration, one project of the five funded under the U.K. Government Future Climate For Africa (FCFA) program, IMPALA (Improving Model Processes for African Climate), had a specific mandate to bring about a step change in pan-Africa model improvement and evaluation (James et al. 2018). The remaining four were transdisciplinary, delivering climate change research and bringing innovative co-production of climate information and services in East, West, Central, and southern Africa through pilot studies. The IMPALA project has targeted effort on some of the important challenges to improved model performance. A major focus has been on understanding the sensitivity of model climate predictions to the representation of mesoscale features, particularly tropical convection or "storm" cells. Research studies and weather forecasting over Africa have made use of models that explicitly capture convection for some years (see the "Science discoveries" section). However, in the global and regional models commonly used to inform adaptation, such as from the Coupled Model Intercomparison Project (CMIP) or Coordinated Regional Climate Downscaling Experiment (CORDEX), only the bulk effects of convection over the model grid scale (typically hundreds of kilometers) is inferred through parameterization. The impact this may have on the realism of climate scenarios is not sufficiently understood, but idealized studies (e.g., Coppin and Bony 2018) have shown there may be significant interactions between convective and climate change time scales, and past studies from other continents have shown significant impacts on the climate change in extremes (Prein et al. 2015).

As a central tool to further investigate the role of moist convection, IMPALA has produced the first-ever convection-permitting multiyear regional climate simulation on an Africa-wide domain using the Met Office Unified Model (CP4-Africa; Stratton et al. 2018; Kendon et al. 2019). These high-resolution (4.5-km grid spacing) simulations, completed for two 10-yr periods representative of present-day and year 2100 climates, explicitly model convection and show significant improvements in representing regional-scale circulations and small-scale climate processes compared to coarser-resolution simulations with parameterized convection (e.g., Stratton et al. 2018; Berthou et al. 2019b; Finney et al. 2019; Hart et al. 2018; Jackson et al. 2019). CP4-Africa shows improved representation of the spatiotemporal characteristics of rainfall and this in turn improves the models capability to represent, for example, land–atmosphere feedbacks and local storm dynamics, which are potentially so crucial for reliable future projections of climate change.

Under FCFA, IMPALA has delivered CP4-Africa data to the four regionally focused projects: in West Africa, AMMA-2050 (African Monsoon Multidisciplinary Analysis 2050); in East Africa, HyCRISTAL (Integrating Hydro-Climate Science into Policy Decisions for Climate-Resilient Infrastructure and Livelihoods in East Africa); in Central and southern Africa, UMFULA (Uncertainty Reduction in Models For Understanding Development Applications); and in southern African cities, FRACTAL (Future Resilience for African Cities and Lands). The projects have provided detailed regional assessment of the model capabilities (Berthou et al. 2019b; Finney et al. 2019; Hart et al. 2018; Finney et al. 2020a; Crook et al. 2019) and used the CP4-Africa simulations to deliver new information on projections and impacts for sectors such as agriculture and water resources. Much of the detailed work of the five FCFA projects is now appearing or is about to appear in the scientific literature and we do not attempt to reproduce it here. Rather, the goal of this paper is to highlight the value of such an integrated framework, including focused model improvement as well as user engagement and service coproduction both for understanding and development within the science community and for delivering useful relevant advice to decision-makers. We will make the case for continued funding for such end-to-end programs and for convection-permitting simulations, highlighting how in even short (4-yr) programs such as FCFA real benefits can be felt on the ground in Africa.

Experimental design and data availability

Designing, building, testing, and production of these pan-Africa, high-resolution simulations took a large amount of people effort—being both supercomputer-hungry and data heavy. We were able to build on the Met Office Unified Model (UM) system utilizing preexisting regional convection-permitting model (CPM) configurations at kilometer-scale resolutions for Lake Victoria as well as over the United Kingdom and other tropical regions. A very wide range of sensitivity tests to aspects of the physics and dynamics, lateral boundaries, etc., were required (Stratton et al. 2018) and have provided valuable lessons for the regional modeling community.

Experimental design. Two regional climate model configurations (CP4-Africa and R25) have been run using the UM, which is a nonhydrostatic model with a semi-implicit, semi-Lagrangian dynamical core. Lateral boundary conditions were driven by a global N512 (~40-km resolution at the equator) UM simulation with observed sea surface temperatures (SSTs). The regional domain extended from 45°S to 40°N and from 25°W to 56°E to include the whole of continental Africa (domain shown in Fig. 1).

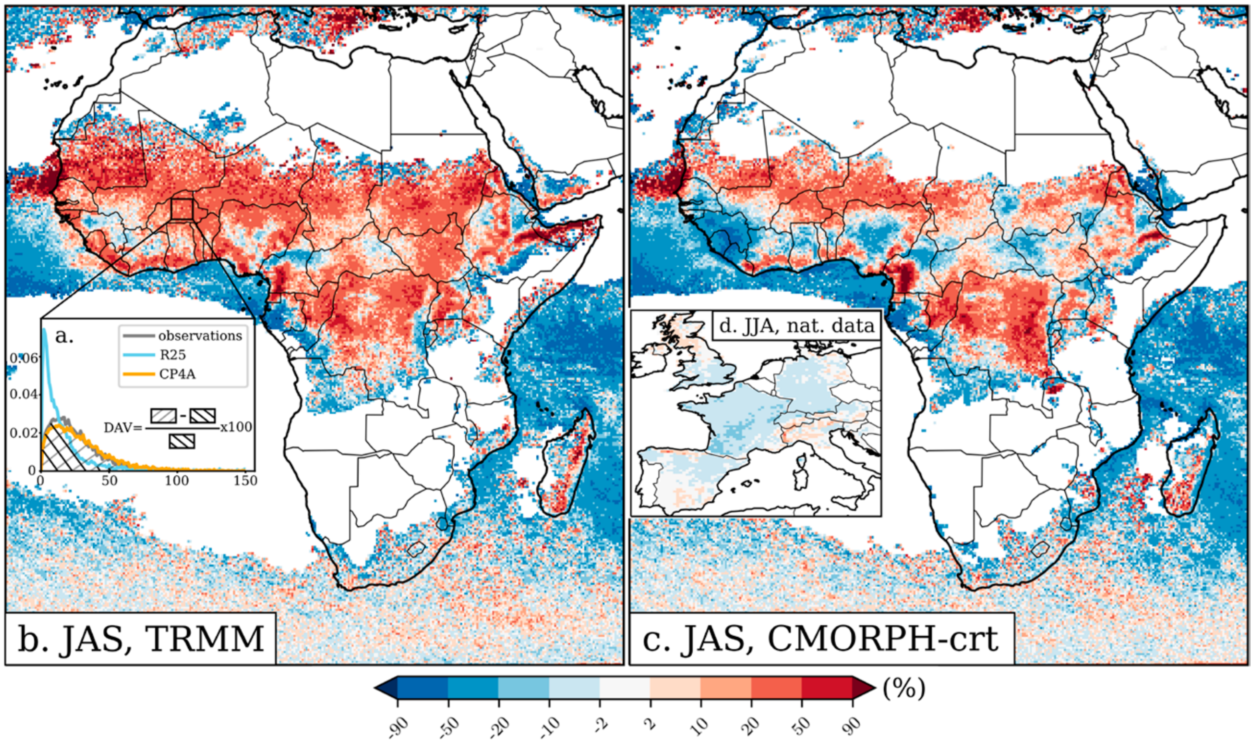

Fig. 1. Distribution added value (DAV) as defined by Soares and Cardoso (2018). (a) Method: fractional contribution of regular 1 mm day^{-1} bins. The frequency in each bin is multiplied by its precipitation rate and then normalized by mean precipitation. The overlap between each model and the observations is taken, and the DAV is the difference of overlap between CP4-Africa and the observations on the one hand and R25 and the observations on the other hand, normalized by the latter. (b) DAV at every single grid point for July–September daily precipitation distribution in CP4-Africa and R25 compared to TRMM observations. (c) As in (b), but compared to CMORPHv1-crt observations. (d) DAV calculated over Europe with a similar model setup run at 2.2- and 25-km resolutions against national datasets (Berthou et al. 2020). The DAV is positive (red) when the precipitation distribution of the CPM overlaps more with the observations than the convection-parameterized model.

CP4-Africa used a horizontal grid spacing of ~4.5 km at the equator and 80 vertical levels up to 38.5 km. Convection was represented explicitly using the model dynamics and included stochastic perturbations in the subcloud layer of cumulus-capped boundary layers to improve the triggering of resolved convection. R25 used a horizontal grid spacing of ~25 km and 63 vertical levels up to 41 km. Parameterized convection was based on the Gregory–Rowntree mass flux scheme (Gregory and Rowntree 1990) with several enhancements, including allowance for downdrafts, different entrainment rates for shallow and deep convection, convective momentum transport, and a closure based on convectively available potential energy (Walters et al. 2017). Uniform sandy soil properties were imposed in both regional configurations, CP4-Africa and R25. This is primarily to mitigate against heterogeneity in the soil texture map influencing the pattern of soil moisture and surface fluxes and subsequent initiation of convection (Taylor et al. 2013). The choice of sandy soil properties represent those across much of West Africa and avoid the known shortcomings of empirical relationships to represent tropical weathered soils such as those found in central Africa. In addition to differences in model resolution and the representation of convection, other notable differences between CP4-Africa and R25 include differences in their cloud and boundary layer schemes (Stratton et al. 2018).

The present-day climate simulations for CP4-Africa and R25 were run for 10 years (1997–2006). The simulations were forced with SSTs derived from the Reynolds dataset of daily high-resolution blended analyses for SST on a regular spatial grid of 0.25° resolution (Reynolds et al. 2007). Atmospheric greenhouse gas (GHG) concentrations had fixed global values that were updated annually and aerosol concentrations were based on climatologies based on the CLASSIC (Coupled Large-Scale Aerosol Simulator for Studies in Climate) aerosol scheme (Walters et al. 2017). The future climate simulations were run for a period of 10 years using the same design as used for the present-day climate simulations, except for a different driving simulation and changes to the GHG concentrations and SSTs. GHG concentrations were taken from ~2100 in projections of Representative Concentration Pathway 8.5 (RCP8.5) (Moss et al. 2010). Lateral boundary conditions were taken from a global simulation driven by observed SSTs plus the climatological average SST change between 1975–2005 and 2085–2115 in an earlier UM model, HadGEM2-ES (Collins et al. 2011), RCP8.5 simulation. SST changes in CP4-Africa were the same as those of the driving global simulation. The same aerosol and ozone climatologies were used in the present-day and future climate simulations. See Kendon et al. (2019) for further details.

Most analysis has used the CP4-Africa data regridded to 25 km, with conservation of mean properties. Precipitation at a 4.5-km grid scale is known to be too intense and localized (Berthou et al. 2019b), a common problem of CPMs. Further work is identifying where the sub-25-km-scale pattern of projected changes in rainfall events may be robust, e.g., in regions of large mountains, narrow ridges, coastlines, or large urban areas.

Data availability. Over 2 Pb of data have been produced from the two 10-yr CP4-Africa simulations. All the data are now permanently stored at the Met Office. However, during the project, we needed to share CP4-Africa data as the simulations progressed with partners in the regional FCFA projects to enable broader assessment and use in trial services. This was first achieved at small scale by sharing small amounts of data via hard drives and/or remote access to U.K. university computer systems, and later through access to the JASMIN infrastructure run by the Centre for Environmental Data Analysis (CEDA). FCFA researchers have accessed data directly from the Met Office data holdings and uploaded to JASMIN, a U.K.-based petascale analysis facility for data-intensive environmental science, where they share a group workspace for analysis and data manipulation. We are currently broadening this access to a wider range of researchers, notably those in Africa, and have produced a technical guidance note for those using the data (Senior et al. 2020). Access will have two routes. The first is to enable more researchers to utilize the power of JASMIN functionality and the very large datasets. There are significant challenges in doing this outside of the United Kingdom, which we are working to improve. The second is a now publicly available, user-friendly data download facility based at CEDA for the key variables that we hope will cover a high percentage of user needs (https://catalogue.ceda.ac.uk/uuid/a6114f2319b34a58964dfa5305652fc6). We hope this easy-to-use data access will enable wider analysis of these unique simulations.

Science discoveries

While convection-permitting simulations are becoming more widely used for climate research and prediction (Prein et al. 2015; Kendon et al. 2020), the CP4-Africa simulations are unique in being convection-permitting simulations on climate time scales (present and future) on a large domain over tropical land. The value of convection-permitting modeling over West Africa was pioneered by the Cascade project (Pearson et al. 2010; Marsham et al. 2013). Using the UM, Cascade showed that not only did explicit convection improve rainfall intensity, diurnal cycle, cold pools, and storm propagation, together with land–atmosphere interaction, but also, through upscale impacts, it improved continental-scale circulation and water budgets (Marsham et al. 2013; Birch et al. 2014a,b; Taylor et al. 2013) as well as crop and dust models (Garcia-Carreras et al. 2013; Marsham et al. 2011; Heinold et al. 2013). Many studies, using a range of models run for different time scales, have now shown that explicit convection greatly improves modeled storm life cycles in Africa; many of these have, however, also noted that capturing the observed population of storm sizes, lifetimes, and speeds, as well as cold-pool intensities, remains challenging (Birch et al. 2012; Beucher et al. 2014; Chaboureau et al. 2016; Roberts et al. 2018; Maurer et al. 2017; Vizy and Cook 2019). It has now been demonstrated that explicit modeling of West African storms can improve midlatitude weather forecasts (Pante and Knippertz 2019). For East and southern Africa, convection-permitting models have been shown to improve regional numerical weather prediction (Woodhams et al. 2018; Stein et al. 2019). Furthermore, a CORDEX flagship pilot study of convection-permitting models over the Lake Victoria region is now underway with simulations similar to those of Van de Walle et al. (2020). Global convection-permitting modeling is now possible (Judt 2018; Stevens et al. 2019) and time-slice climate change experiments have been performed (Satoh et al. 2018) but even with modern computer power, grid spacings and run durations are limited, and analysis of such runs has not focused on Africa. CP4-Africa shows many of the conclusions from past studies on improvements at both storm and continental scales from using convection-permitting models to be robust (Stratton et al. 2018; Berthou et al. 2019b; Kendon et al. 2019; Finney et al. 2019; Crook et al. 2019). Furthermore, CP4-Africa alters the balance of rain between the Congo basin and East Africa, although this may contribute to a wet bias over the Lake Victoria basin (Finney et al. 2019). By generating a stronger vertical mass flux in the tropics, CP4-Africa enhances upper-level subsidence in the subtropics, amplifying the forcing of the local subtropical jet, which halves the wet subtropical rainfall bias and improves the annual cycle of tropical–extratropical cloud-band rainfall (Hart et al. 2018), a primary rain-bringing system in southern Africa.

An example of the improvement for current climate seen in CP4-Africa is shown in Fig. 1, which presents the distribution added value (DAV) as defined by Soares and Cardoso (2018) (Fig. 1a). This provides a percentage of improvement (positive values in red) or deterioration (negative values in blue) of the distribution of daily precipitation values by the CPM. We use both the Tropical Rainfall Measuring Mission 3B42v7 (TRMM 2011) and CMORPHv1-crt (Xie et al. 2017) as reference datasets, as they exhibit different strengths and weaknesses. Against TRMM (Fig. 1b), CP4-Africa shows a large improvement of the precipitation distribution over tropical land in July–September (JAS; also true in other seasons, see Fig. S1 in the online supplemental material). In the Sahel, this is in part due to a better representation of the life cycles of mesoscale convective systems (MCSs) (Crook et al. 2019). The noticeable impact on the coasts throughout the year (in JAS on the southern coast of West Africa but on other coasts in other seasons; Fig. S1) also suggests widespread improvement in coupling between land–sea breeze and convective activity in CP4-Africa [seen in Finney et al. (2019) for East Africa]. Over the ocean, CP4-Africa overestimates the intensity of rainfall (although, observations are weakly constrained by gauges there). This is consistent with a lack of ocean–atmosphere coupling in CP4-Africa (Hirons et al. 2018), or that the convection-permitting model does not correctly model shallow convection and tends to have more precipitation from deep convection, in line with Becker et al. (2017). Further research is needed to fully understand this particular bias over the ocean. Against CMORPH (Fig. 1c), most conclusions remain valid but the improvement in tropical Africa is smaller: CP4-Africa tends to overestimate precipitation intensity against this dataset whereas it agrees better with TRMM (Berthou et al. 2019b).

In comparison to midlatitudes, there is a much greater improvement in the tropical daily precipitation distribution at convection-permitting resolution, as can be seen by comparing Figs. 1b and 1d, where the same metric is shown for a European 2.2-km model, the global 25-km driving model, and national gauge-based gridded datasets (detailed in Berthou et al. 2020). In Europe, improvements in the distribution in the CPM are mostly realized at the subdaily time scales (Berthou et al. 2020). In Africa the improvements are similar at subdaily time scales (not shown).

The more intense and intermittent nature of rainfall in CP4-Africa has a pronounced impact on the land water budget. The fraction of rainfall in densely vegetated regions that is intercepted by the canopy and evaporated back into the atmosphere falls from 22% in R25 to less than 6% in CP4-Africa (observations from tropical forests suggest values of 9%–13%; Miralles et al. 2010). The change is due to large differences in the frequency of light rainfall between the models. These differences alter the partition between sensible and latent heat fluxes on time scales of hours to weeks, in turn feeding back on atmospheric circulations.

CP4-Africa has also provided unique insights into climate change: physical understanding of differences in projected changes between CP4-Africa and R25 shows that some differences are likely relevant to all parameterized models and so must be considered in decisions informed by CMIP and CORDEX. In common with past midlatitude studies (Prein et al. 2015), explicit convection gives a greater increase in extreme rain (Kendon et al. 2019; Berthou et al. 2019a). This is a result of a greater intensification of updrafts and a greater modulation of available water by storms in CP4-Africa, as well as an inability of R25 to capture changes in rain frequency, and, in East Africa at least, R25's changes in extreme rain being more tied to fixed mesoscale forcings (Jackson et al. 2020; Finney et al. 2020a). The scaling coefficients of extreme precipitation change are poorly correlated between CP4-Africa and R25 ($r < 0.4$; Kendon et al. 2019), especially at high temperature changes, showing that future changes in extremes cannot be simply inferred statistically from R25. CP4-Africa also has a greater increase in dry spells during the wet season in the Sahel, which is linked to an increase in convective inhibition, which gives a suppression of future afternoon initiating storms compared with self-organized overnight MCSs, while R25 fails to capture this diurnal cycle (Kendon et al. 2019).

CP4-Africa gives a greater and more realistic response of updraft strength to shear than R25 (Fitzpatrick et al. 2020b). On the other hand, CP4-Africa does not capture the observed increases in MCS rainfall intensities with wind shear (cf. Figs. 2a,b), implying that further model development is needed. However, by 2100, the projected changes in the drivers of MCS intensity are dominated by increased atmospheric moisture content (Fitzpatrick et al. 2020b), for which CP4-Africa and observations show very good agreement in scaling MCS intensity; e.g., Figs. 2c and 2d show how maximum precipitation and cloud-top temperature scale with low-level humidity at very similar rates in CP4-Africa and observations. This provides some confidence in the magnitude of projected moisture-related MCS changes.

CP4-Africa shows that explicit representation of convection affects climate change at scales much larger than the cumulonimbus scale. There is a greater slowdown in the mean Hadley ascent in CP4-Africa compared with R25. The increase in rainfall under climate change is associated with intensified updrafts and higher total column humidity. The greater intensification of convective updrafts in CP4-Africa yields greater diabatic heating for a given rate of large-scale ascent (Jackson et al. 2020), coupling changes in storm updrafts with the changes in the Hadley circulation. At the 150-km scale resolved by both models, changes in mean rainfall are reasonably well correlated between R25 and CP4-Africa ($r = 0.77$; Jackson et al. 2020), showing the dominance of the parent global model, and the necessity of accounting for global uncertainty in local projections of mean change. There are, however, significant differences; e.g., CP4-Africa gives a greater rainfall increase over East Africa and less over the Congo (Finney et al. 2020a). On the mesoscale, Finney et al. (2020a) shows that although R25 captures lake and sea breezes, its convective response to these features can be limited by a poor representation of the diurnal cycle—with peak convection strongly tied to local noon. This is significant given Africa's highest population growth is on the coast (Neumann et al. 2015), and we expect similar effects in other parameterized models. CP4-Africa shows larger changes in intraseasonal rainfall variability in the West African Sahel with climate change, and this is not usually accounted for in impact models (Berthou et al. 2019a) and can affect changes in seasonality, false-onset, onset, and cessation (Wainwright et al. 2021; Fitzpatrick et al. 2020a).

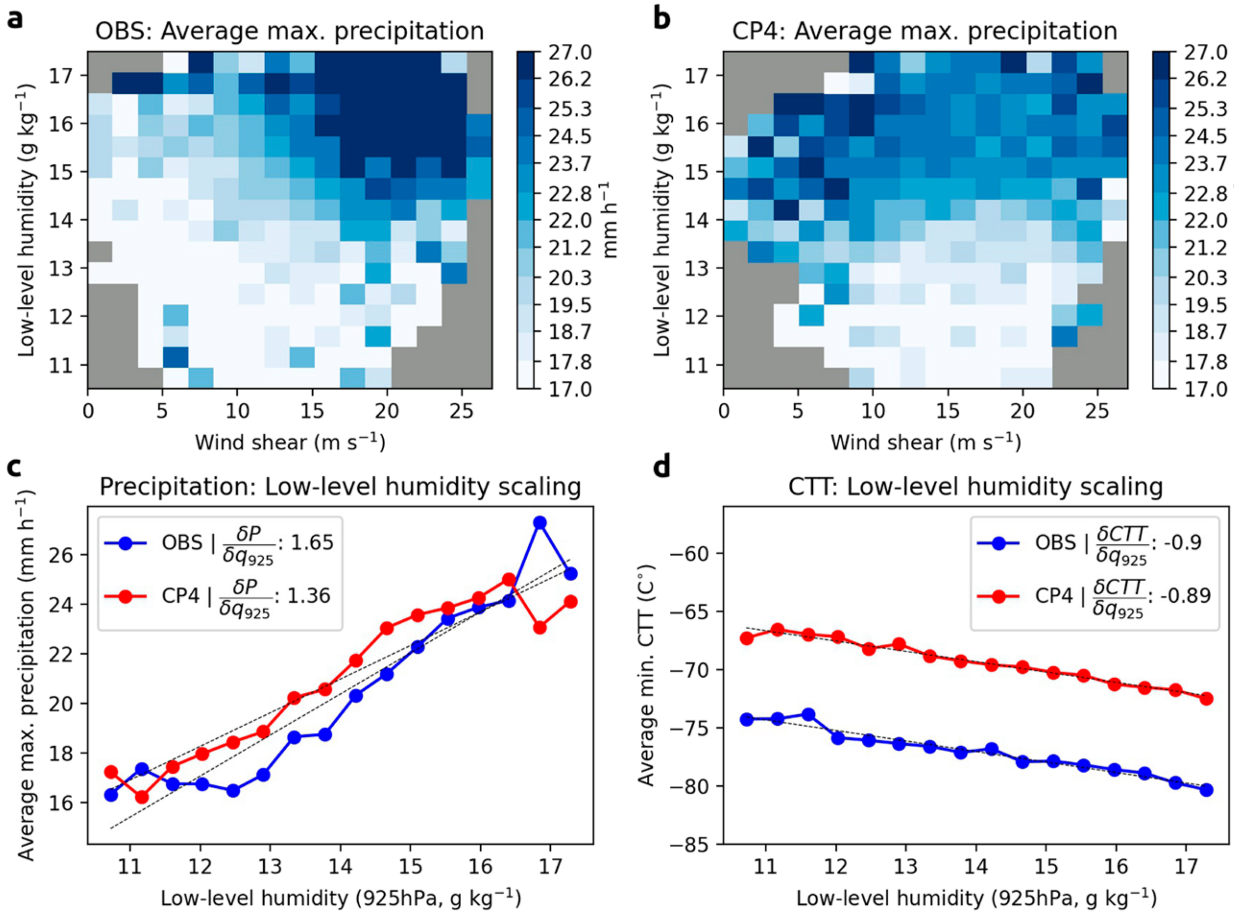

Fig. 2. MCS intensity scaling with atmospheric drivers for the CP4-Africa historical period and observations. Two-dimensional histograms for average maximum precipitation of (a) OBS and (b) CP4-Africa as a function of prestorm (1200 UTC) 925-hPa specific humidity and 650–925-hPa absolute zonal wind shear at storm location for >24,000 afternoon (1600–1900 UTC) MCSs over the Sahel (9–19°N, 12°W–12°E). Bins with *n* < 10 MCSs are shaded gray. (c) The average maximum precipitation for OBS (blue) and CP4-Africa (red) associated with humidity bins in (a) and (b). (d) As in (c), but for minimum cloud-top temperature (CTT). Legends show the slope of the linear fit (dashed lines). OBS combines ERA5 hourly data (wind shear and humidity), Meteosat Second Generation brightness temperatures (CTT, MCS defined as ≥5,000 km^2, ≤–50°C), and IMERG High Quality precipitation estimates (1-mm minimum rainfall threshold) for 2004–17.

Research on climate impacts modeling using CP4-Africa is ongoing, but so far shows mixed value, depending on application. For the strong winds that generate dust from the Sahel and Sahara by capturing cold pools ("haboobs"), CP4-Africa shows a greatly improved annual cycle compared with R25. However, it is the sensitivity of changes in synoptic-scale winds to explicit convection that controls the difference in the models climate change response in strong winds, with this outweighing effects of changes in haboobs themselves (Garcia-Carreras 2021, manuscript submitted to *Climate Atmos. Sci.*). For a simple crop suitability model, uncertainty is dominated by the spread in projections shown by CORDEX and CMIP, but when effects of extremes are included, CP4-Africa makes an increased, but still small, contribution, showing the need for improved knowledge of sensitivity to extremes for African crops to make best use of new-generation simulations such as CP4-Africa (Chapman et al. 2020). For lightning, which is parameterized in CP4-Africa but not R25, opposite changes in lightning days and intensity lead to little change in total flashes under climate change, unlike the increases shown in many past studies (Finney et al. 2020b). Finally, we note that improvement from explicit convection is not universal; for example, there is overintense rainfall in CP4-Africa. Notably, CP4-Africa does not significantly improve rainfall response to Kelvin waves, which are a major mode of variability in the tropics, although the dry-spell response is improved (Jackson et al. 2019).

The analysis of CP4-Africa has highlighted considerable new information and improved capability, but also exposed remaining biases. CP4-Africa is also only driven by a single global model; therefore, for decision-making, it should always be considered together with information from other contemporary models, such as those from CMIP and CORDEX. Despite evidence that parameterization of convection causes systematic bias in large-scale change (Jackson et al. 2020), uncertainty in the change in the mean state tends to be dominated by the spread in these ensembles, but for extremes systematic differences between CP4-Africa and R25 are relevant to all models in such ensembles. Examples of applications of CP4-Africa are discussed in the next section.

User benefits and impact

Using CP4-Africa to develop information for decision-making. Rapid pull-through of the new CP4-Africa dataset and science understanding into user application was an important goal of the FCFA program, and this has been achieved through strong collaboration between the five projects under FCFA and significant interdisciplinary work within each of the four regional projects, which each ran pilot studies to include climate change information in long-term decision-making (5–40 years) in Africa. The new insights provided by CP4-Africa have led to its use in the climate information provided in many of these pilots. In HyCRISTAL it is being used to inform flood risk modeling for urban Water, Sanitation and Hygiene (WASH) planning in East African cities, in a joint pilot study with UMFULA on tea production (Mittal et al. 2021, manuscript submitted to *Climate Risk Manage.*), and in the HyCRISTAL Transport Pilot Project (HyTPP) to study plausible future Lake Victoria levels to inform transport policy. In AMMA-2050 it is being used for urban flood planning in Ouagadougou (J. Miller 2021, unpublished manuscript). In UMFULA it is being used to inform agricultural planning in Tanzania and for a project on wildebeest migration. In both FRACTAL and HyCRISTAL it is informing decision-making using the climate risk narrative (CRN) process (Jack et al. 2020) along with, and in the development of, infographics and supporting climate information in text and graphical formats. Here we briefly describe three of these applications.

Flood risk in Ouagadougou. In West Africa, the trend toward a more extreme climate (Panthou et al. 2014; Taylor et al. 2017; Panthou et al. 2018; Wilcox et al. 2018; Nka et al. 2015) is pushing decision-makers to define relevant mitigation and adaptation strategies to protect a rapidly growing population from hydrological hazards. It also challenges scientists to provide decision-makers with tangible information on climate change and its local and regional hydrological impacts.

The AMMA-2050 project has tackled these issues by adopting a co-construction approach with decision-makers and hydrological risk managers in the city of Ouagadougou (capital of Burkina Faso). The city has recently been affected by disastrous floods, most notably on 1 September 2009, when a record rainfall of 263 mm fell on the capital in just a few hours (Lafore et al. 2017; Engel et al. 2017; Beucher et al. 2020). Exchanges with the municipality, the Ministry of Urban Planning and Housing, and their technical services led to the identification of a need to design storm and urban flood maps in present and future climates that could contribute to urban planning and the implementation of the storm water management master plan. These exchanges confirmed the importance of MCSs at the interface between climate change at global and regional scales and their impact on local hydrological systems (Vischel and Lebel 2007). They have led to the implementation of a unique physical and statistical modeling chain of the climate–hydrology continuum to meet the expectations of stakeholders in Ouagadougou (Fig. 3). The originality of this modeling chain lies mainly in the unprecedented opportunity offered by CP4-Africa simulations to explicitly represent the

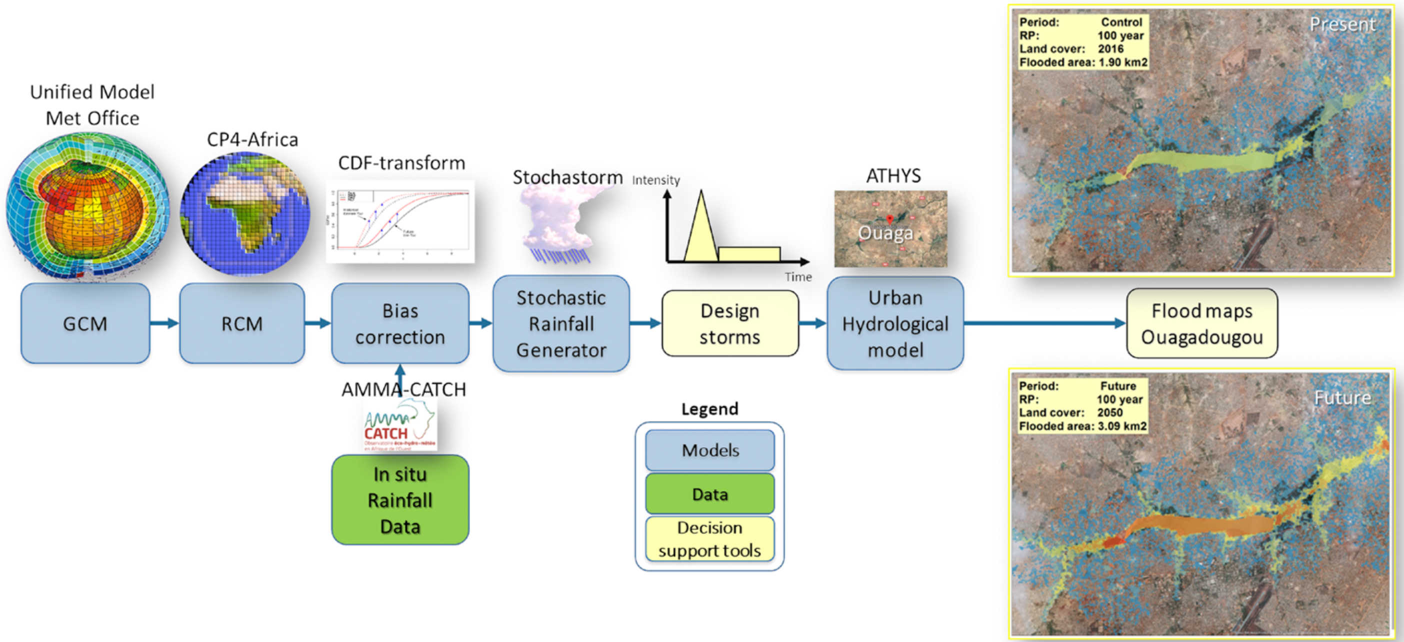

Fig. 3. Modeling chain of the climate–hydrology continuum over the city of Ouagadougou (Burkina Faso). CP4-Africa simulations are used to produce water management decision support tools defined with stakeholders within the AMMA2050 project. The flood maps represent the flooded areas for an estimated 100-yr return design storm based on (top map) CP4-Africa rainfall simulations over the control period and using a land-use–land-cover map from 2016 and (bottom map) CP4-Africa rainfall simulations over the future period and using a land-use–land-cover map projected to 2050.

processes and scales associated with monsoon storms at spatial scales compatible with those required by hydrological models.

The CP4-Africa simulations have been linked to a statistical bias correction method (CDF-Transform; Vrac et al. 2012) based on in situ measurements from the AMMA-CATCH observatory (Galle et al. 2018) to mitigate some of the shortcomings of the representation of spatial intermittency and most extreme rainfall intensities. The bias corrected CP4-Africa simulations are then used to calibrate a stochastic rainfall simulator (Vischel et al. 2009; Wilcox et al. 2021) that generates long chronicles of storms with climatological characteristics similar to those simulated by CP4-Africa. From the stochastic rainfall series, design storms are extracted with various return periods in accordance with decision-makers' expectations (e.g., 100-yr return period in Fig. 3). These design storms then feed an urban hydrology model [Atelier Hydrologique Spatialisé (ATHYS); Bouvier et al. 2018] that allows the generation of flood maps in present and future climates.

The modeling chain results and products are intended to be presented and discussed with the various stakeholders involved in the AMMA-2050 project. The flexible design of the chain is also likely to evolve in order to consider different sources of uncertainty, notably related to the current dependence of CP4-Africa simulations on forcing by a single global climate model (GCM) under the constraint of a single RCP scenario.

Tea production in East Africa. Climate Information for Resilient Tea Production (CI4Tea) combines the CP4-Africa projection with much coarser projections from 29 different GCMs and long-term climate observations from nine tea estates, to form a site-specific Synthesis of the Projected Range (SPR). This SPR is used to produce tailored climate information for Africa's largest tea producing nations—Kenya and Malawi—by iteratively engaging tea supply chain actors including tea estate managers, smallholder farmers, and tea research institutes (stakeholders, hereafter). Tea is a perennial cash crop with a long economic life cycle of up to 100 years, which imposes path dependencies due to limited flexibility in crop management decisions. The climate sensitivity of a tea bush limits its cultivation to regions within the optimum temperature and rainfall range (as well as appropriate soil and humidity conditions). Since each tea growing region experiences unique topographic and climatological complexity, the SPR aims to capture the range of plausible climate change signals for decision-relevant metrics to build site-specific risk profiles for tea estates located in close proximity.

Future projections for a temperature metric [heat wave frequency (HWF)] and the associated uncertainty range based on the SPR with and without CP4-Africa data are shown in Figs. 4a and 4b. The 2050s and 2080s are representative of tea sector planning horizons

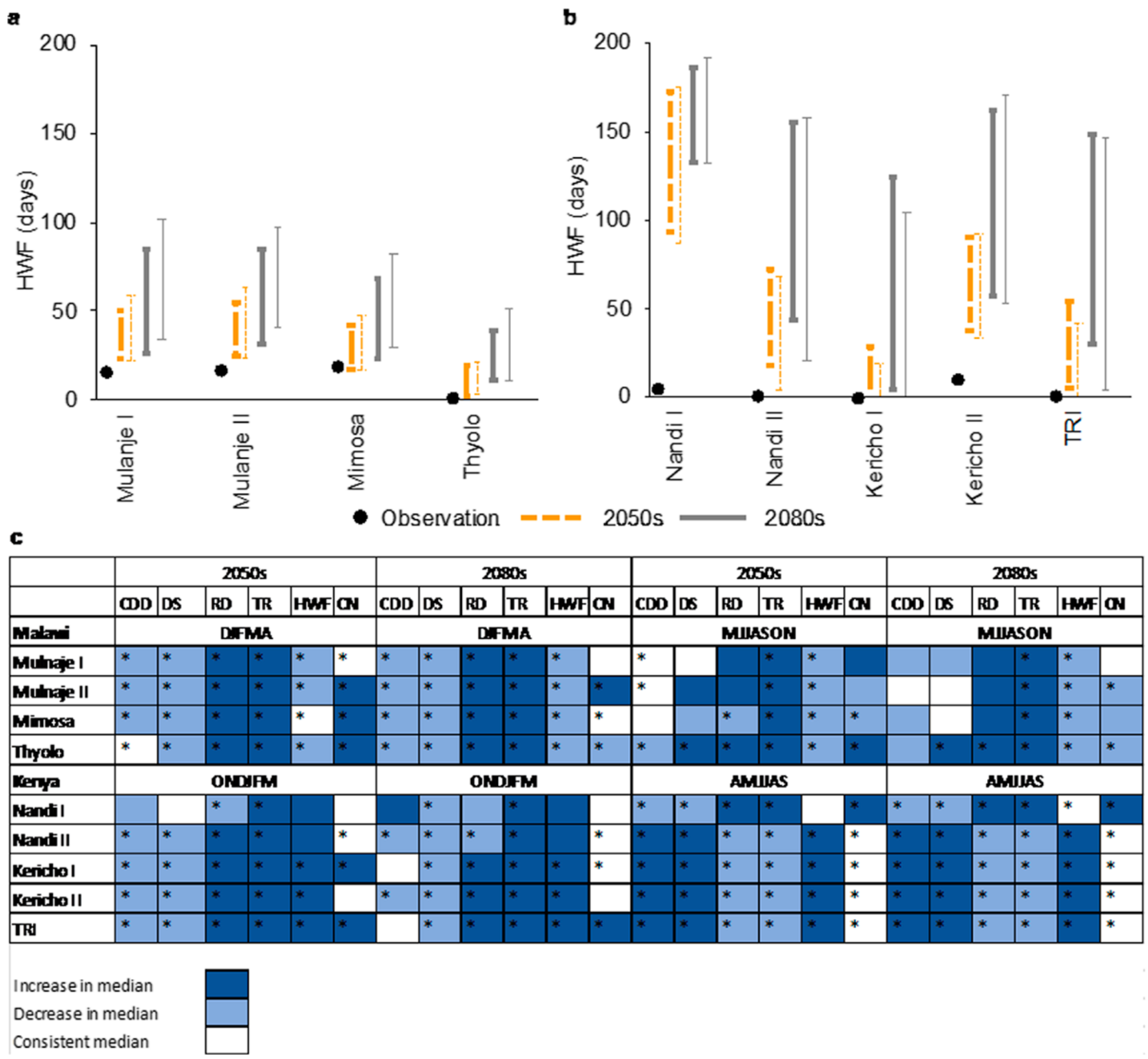

Fig. 4. (a) For Malawi, HWF (total number of days in sequences of 5 or more consecutive days when daily maximum temperatures are all above 35°C) observed (black dots) and projected changes for May–November (MJJASON) season for the midcentury (2050s; colored segments) and end century (2080s; gray segments) show the SPR (±2 standard deviations) at four sites. (b) As in (a), but for Kenya, where the HWF threshold is 27°C and for April–September (AMJJAS) season at five sites. Thinner lines show SPR without CP4-Africa data. (c) Effect of inclusion of CP4-Africa data on the SPR median for decision-relevant metrics for two seasons in Malawi and Kenya. The significance is tested by two-tailed paired *t* tests for mean, indicated by an asterisk (*) when $p < 0.05$ where consecutive dry days (CDD) are the maximum number of consecutive dry days when rainfall $R < 1$ mm, dry-day incidences (DS) when $R < 1$ mm for 10 consecutive days, rainy days per year (RD) when $R > 1$ mm, total seasonal rainfall amount (TR), and cold nights (CN) when minimum temperature <12.5°C (Malawi) and <6°C (Kenya).

for medium- and long-term adaptation decision-making. Projections indicate an increase in heat stress incidences across all sites in Malawi and Kenya compared to recent observations. Moreover, the SPR improves site-specificity of the projections, with the mean change significantly affected (based on two-tailed paired difference *t* tests) by both the CP4-Africa and site observational data at all stations and for all co-developed metrics except for consecutive dry days projections for the 2080s in Kenya (Fig. 4c). Iterative stakeholder engagement, site specificity, climate information for decision-relevant metrics at seasonal scale, and uncertainty communication overcome barriers to use the climate information for adaptation decision-making (Lemos et al. 2012; Mase and Prokopy 2014). The SPR is a transferable methodology that could be used for improving future climate information for other climatic variables critical for sustaining tea yield and quality, or for contributing to more resilient decision-making for other sectors.

Climate risk narratives. FRACTAL has focused on building climate resilience in nine southern African cities through in-depth engagement with national and city institutions and community stakeholders to identify climate risks and generate knowledge informing plans and actions to reduce these risks. Over a series of three Learning Laboratories (platforms for iterative engagement and collaborative learning; Arrighi et al. 2017) in Lusaka, water in peri-urban (or informal) settlements was identified as the overarching burning issue. This comprised interrelated concerns around flooding, sanitation, groundwater recharge, drinking water and solid waste (Mwalukanga et al. 2016). Participants engaged in developing climate risk narratives (Jack et al. 2020) as a key part of exploring the burning issues and as a means to communicate future climate risks, including the development of an infographic (Fig. 5) to summarize these future climates and some of their impacts, related societal consequences and possible responses. The infographic and supporting information were then used to communicate high-level messages to Lusaka and Zambian government ministers and officials and subsequently informed the development of four policy briefs by local stakeholder task teams and FRACTAL partners.

A major recommendation in the brief on flooding was based on analysis of a set of climate projections for the Lusaka region indicating significant reductions in the return periods of extreme rainfall in a future warmer climate (Table 1). These are derived from one global climate model (HadGEM2-ES) and its downscaling over Africa by a 50-km regional climate model taken from the widely used CORDEX-Africa ensemble (e.g., Shongwe et al. 2014; Pinto et al. 2016) and additionally from CP4-Africa and R25. Table 1 shows that the coarser-resolution models tend to underestimate the intensity of rainfall extremes, with the opposite for the higher-resolution R25 and CP4-Africa models with the latter significantly overestimating their intensity. The daily distribution of precipitation in this region is not improved by CP4-Africa (Fig. S1). This overintensification of rainfall in CP4-Africa has also been found for other African regions (Kendon et al. 2019; Berthou et al. 2019b) and is a common deficiency of CPMs due to convection not being fully resolved and updrafts being forced to occur at the model grid scale (e.g., Kendon et al. 2020). In spite of these differences, all of the projections for the future climate indicate significant reductions in return periods by factors mainly in the range of 2–10. It was this clear message that motivated the advice to use the highest standards in new or rehabilitated drainage to protect peri-urban settlements in the future from at least the 1-in-5-yr to 1-in-10-yr extreme rainfall event.

CRNs were also developed and used in HyCRISTAL to represent both plausible rural (Burgin et al. 2019a) and urban (Burgin et al. 2019b) impacts, with full details of the climate information used provided by Burgin et al. (2020). CP4-Africa allowed key statements to be made about future changes in extreme rainfall and dry spells within the rainy seasons, which were made relevant to the stakeholder community through the CRNs. Impacts of changing

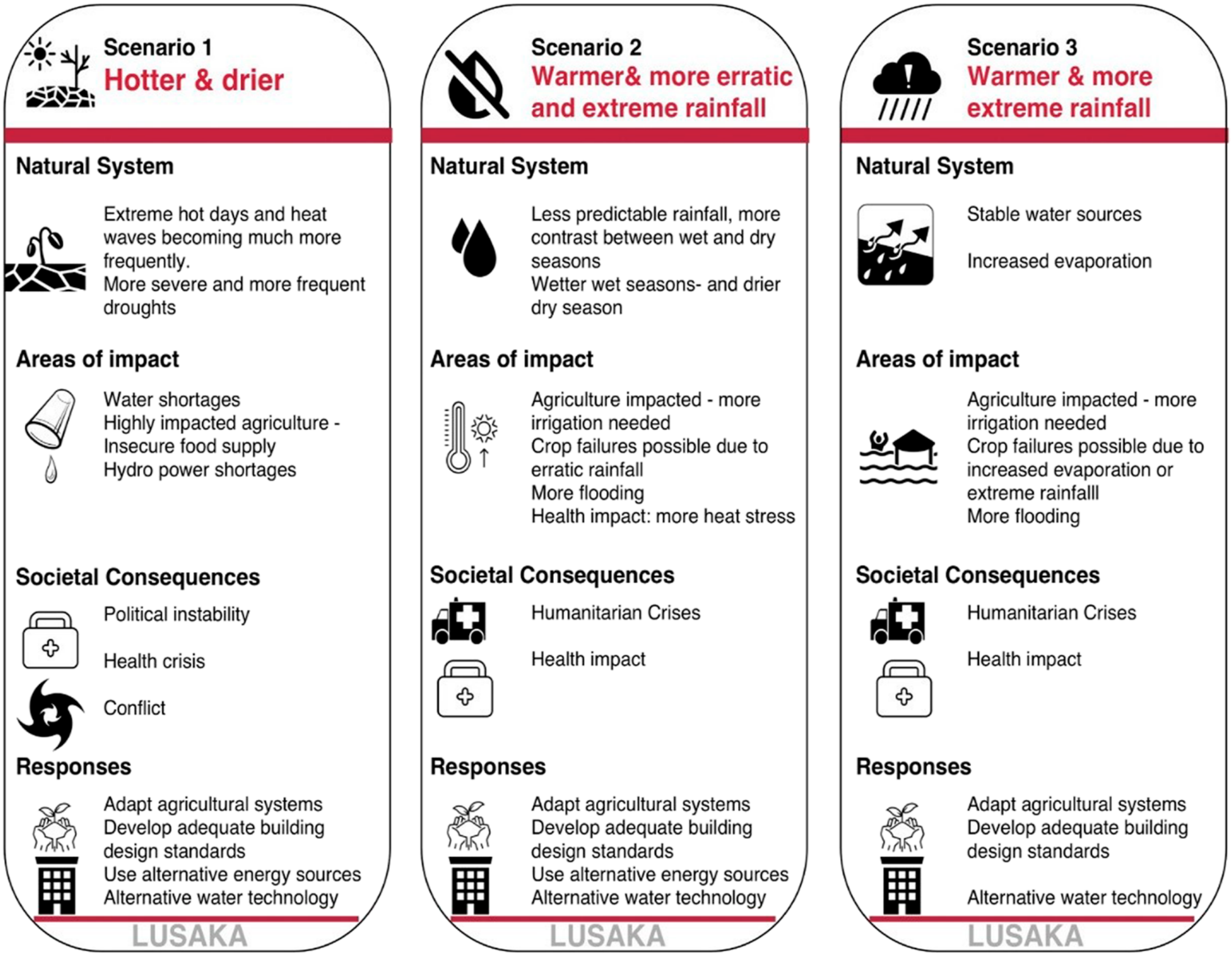

Fig. 5. Infographic summarizing three plausible future climate scenarios for Lusaka along with some key impacts, possible societal consequences, and responses.

rainfall patterns in East Africa, which have high uncertainty, were clearly delineated between different climate futures using the CRN approach and allow for more constructive discussions around adaptation decisions.

The CRNs have also been used during the Greater Horn of Africa Climate Outreach Forum to encourage engagement from the seasonal forecasting community in longer-term climate change decision-making. Additionally, they have been used in the "Future-Climate Current-Policy Framework," where they provide a crucial first step in aiding a stakeholder group to discuss and plan the stages needed to enact adaptation measures in their community (Evans et al. 2020). Finally, the infographics and briefs are among the most downloaded documents from the FCFA website, suggesting, as hoped, they are acting as a long-lasting communication tool.

Feedback on the climate modeling community. Like CP4-Africa, the next generation of weather and climate models, both regional and global (Prein et al. 2015; Satoh et al. 2019), will operate in the so-called "gray zone" of turbulence and convection, which corresponds to model grid sizes of about 200 m to 5 km (Tomassini et al. 2017; Field et al. 2017). In this regime, turbulent and convective motions are partly resolved and partly subgrid. Since the

Table 1. Observation and model-based estimates of the intensities of 5- and 20-yr extreme rainfall events in mm day^{-1} (columns 2 and 4, respectively) and the model-projected return periods of these events in the simulated future climates in years (columns 3 and 5, respectively). The observed estimates were calculated from daily rainfall data recorded at a weather station in Lusaka. The model-based estimates were calculated for the model grid box containing Lusaka (for HadGEM2-ES and 50-km regional model) or for six grid boxes around Lusaka (for R25 and CP4A).

Source of Lusaka rainfall data	Present-day 5-yr event (mm day^{-1})	Future return period (years)	Present-day 20-yr event (mm day^{-1})	Future return period (years)
Observations	89.9	—	112.8	—
HadGEM2-ES	71.2	<1.5	89.9	1.5
50-km regional climate model	76.4	2	104.8	5
R25 (six-box average)	120.7	<1.5	155.9	3
CP4-Africa (six-box average)	205.4	3	271.4	9

subgridscale motions impact the resolved scales, they still need to be parameterized. However, various assumptions of traditional convection and turbulence parameterizations are no longer valid in the gray zone, e.g., the assumption of a quasi-equilibrium between an ensemble of convective clouds and its environment. Thus, for gray-zone model simulations, novel types of scale-aware parameterizations need to be developed (Holloway et al. 2014).

Moreover, since the various subgrid parameterizations in weather and climate models are intimately related and coupled, the gray-zone problem does in fact not only affects subgrid turbulence and convection, but also the parameterization of clouds, cloud microphysics, radiation, and surface processes. A consistent and, where possible, unified formulation of subgrid schemes therefore becomes paramount. Thus, development of gray-zone CPMs will require a rethink and rebalancing of the entirety of the physics parameterizations. Certain schemes may become simpler and more efficient, while more emphasis will have to be placed on, e.g., the modeling of cloud microphysics or the three-dimensional representation of turbulence and radiation.

Apart from physical subgrid parameterizations, high-resolution CPMs also necessitate developments related to the dynamical core of the model. For example, traditional, nonconservative semi-Lagrangian advection schemes can cause serious issues when it comes to the explicit simulation of deep convective systems, particularly in the tropics.

The parameterization of vegetation canopy interception and surface runoff has been developed over the years to deal with frequent, low-intensity rainfall typical of the output from convection parameterization schemes used in traditional coarse-resolution climate models (Dolman and Gregory 1992). These schemes assume a subgrid distribution of rainfall intensity in order to reduce interception loss and to enhance surface runoff. Both the CP4-Africa and 2.2-km European climate simulations have highlighted that the use of these subgrid distribution schemes needs to be reconsidered at convection-permitting resolution as they can lead to accumulating biases in soil moisture, which feed back on the atmosphere (Berthou et al. 2020). A second land-related aspect of CPMs arises from the increased contribution to rainfall from surface-forced mesoscale circulations (Taylor et al. 2013; Finney et al. 2020a). In many regions of the world, and in Africa in particular, the quality of soil and vegetation maps at the mesoscale is often poor. Moreover, there are missing hydrological processes in many land models (e.g., inundation and groundwater dynamics), which become important at kilometer scale. These issues need to be addressed if planners are to benefit from the high-resolution rainfall projections that CPMs can provide, for example, along the often densely populated coastlines of Africa.

In all of these areas, the CP4-Africa simulation has pioneered approaches or helped to highlight issues that demand further work and effort (Stratton et al. 2018). Through the sensitivity experiments during the development of the model configuration, as well as the subsequent detailed analysis of the simulation and confrontation with observations, CP4-Africa has informed model development not only over Africa, but more widely, and for the first time on a decade-long time scale, over tropical land regions. It has provided a first reference for how CPMs represent tropical mesoscale convective systems and the interaction of moist convection with the atmospheric circulation on climate time scales. At the Met Office, the simulation was a corner stone in the development of the first science configuration of a regional version of the Unified Model for the tropics (Bush et al. 2020), and continues to support the development of the next-generation global configuration of the Met Office Unified Model.

Is this the future?

The Future Climate for Africa program took the bold decision to support a dedicated project driving improvement in modeling of African climate and, as part of this project, to fund a pair of climate-length simulations with an experimental convection-permitting model with the hope of gaining both scientific insight and new information on user-relevant time and space scales. The scientific investment in the model and the simulations has been considerable. The IMPALA simulations have built on the pioneering work of the earlier Cascade project (e.g., Pearson et al. 2010; Marsham et al. 2013), and many lessons have been learned throughout both projects on the capability of models with a grid spacing of a few kilometers to adequately model convection explicitly, the design of the experiments, and how to usefully interpret the new data and combine it with existing knowledge and information from conventional climate models with parameterized convection. With this hard-gained knowledge and evidence of greater realism, we feel that the time is now right to grow the activity of climate-length simulations with convection-permitting models beyond the experimental and into the mainstream. Such ideas are starting to be taken forward at a modest scale within CORDEX, and we believe they would deliver broad benefits to the international modeling, wider academic, and downstream user communities. A notable benefit is testing the robustness of future climate projections to feed into the Intergovernmental Panel on Climate Change (IPCC) process for vulnerable regions of the world, such as Africa. In the United Kingdom, the latest national climate projections (Murphy et al. 2018) include climate scenarios at convection-permitting scale for the first time. Projects such as IMPALA are showing the potential value that projections at these scales could deliver for Africa (perhaps through an ensemble of simulations at convection-permitting scale) to help provide locally relevant information on risks of future extreme weather to inform planning and decision-making.

Under FCFA, we have demonstrated the value of this ambitious program, but the runs are somewhat idealized, having only been done with one model and for a single ensemble member. Two CORDEX Flagship Pilot Studies programs (CORDEX-FPS) are first attempts to build an ensemble of different CPMs over a greater Alpine region (Coppola et al. 2020) and the Lake Victoria basin (https://ees.kuleuven.be/elvic/). We encourage the international modeling community to coordinate discussion of similar experimental design in the tropics with a goal to deliver to the scientific community, e.g., through IPCC and to decision-makers on the ground.

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