Monograph:

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Scientific Understanding of East African climate change from the HyCRISTAL project

Integrating Hydro-Climate Science into Policy Decisions for Climate-Resilient Infrastructure and Livelihoods in East Africa (HyCRISTAL) is a Future Climate for Africa (FCFA) project funded to deliver new understanding of East African climate change and its impacts, and to demonstrate use of climate change information in long-term decision-making in the region. Here, we briefly summarise key findings from HyCRISTAL so far on climate change, as well as key findings from the pan-African FCFA project "IMPALA" relevant to East Africa, both in the context of previous literature on the topic.

Key conclusions from HyCRISTAL climate science

- New pan-Africa high-resolution (4.5 km) convection-permitting future climate simulations available from IMPALA show, for a single realisation of global change, a greater increase in extreme rainfall than equivalent lower resolution runs (Kendon et al., 2019; Finney et al., 2019c). This shows that larger and more widespread changes extreme rain, than those from CMIP & CORDEX, should be anticipated.
- It is still unclear if rainfall will increase or decrease, but the largest projected increase in the East African long rains from CMIP is implausible (Rowell & Chadwick, 2018; Rowell, 2019)
- Deepening of the Saharan Heat Low under climate change is expected to lead to a later and longer short rains, with a larger rainfall increase than the long rains, with an earlier end to the long rains, although differences between models shows that changes to both onset and cessation are still uncertain in both seasons (Dunning et al., 2018)
- CMIP is not expected to cover the full range of possible change to future rainfall, as future aerosol emissions may induce changes not addressed by CMIP, especially to onset of the short rains (Scannell et al., 2019)

HyCRISTAL climate science methodology

- ❖ Understand past rainfall changes and processes driving them
- ❖ Quantify uncertainty in existing model projections (CMIP) for metrics relevant to East Africa
- ❖ Understand uncertainty in CMIP changes and try and narrow this through evaluation of processes causing that spread
- ❖ Quantify and understand the role of processes not captured or well captured by CMIP: Moist convection, lake-atmosphere interaction, land-use change, aerosol changes

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Climate change in East Africa

Under climate change, temperatures worldwide are expected to increase, total global rainfall is expected to increase, and individual rain events expected to become more intense. However, on a regional basis, some places will warm faster than others, regional rainfall totals may increase or decrease, rain may become more or less frequent, rainy seasons may shift or change in length, and individual rain events may intensify by larger amounts in particular places. Because of such variation in regional responses even across Africa, dedicated study of the East Africa region is necessary.

However, modelling uncertainty means that East Africa's decision-makers need to consider a range of possible futures. HyCRISTAL's summary of possible futures of East African climate are represented as narratives, developed iteratively with users, and usable by a broad range of user groups (Burgin et al. 2019a,b).

The starting point for HyCRISTAL analysis is the most comprehensive data source for quantitative climate change information, the Coupled Model Intercomparison Project 5 (CMIP5). This dataset uses state-of-the-art climate models from around the world to simulate climate change under a number of future scenarios. These scenarios are used to represent the possible paths that humans may take which affect the emissions of greenhouse gases. They range from a low emission scenario (called RCP2.6) to high emission scenario (called RCP8.5). The low emission scenario represents unprecedented, and currently unlikely, reductions in global greenhouse gas emissions, while the high emission scenario represents a high-end, business-as-usual case. Whilst politicians pledged at the United Nations conference in Paris 2015 to reduce emissions, this was not by enough to meet their target temperature rise of no more than 1.5 to 2°C. Global emissions are still rising and therefore still not deviating from the business-as-usual path.

An East Africa focus on existing climate change data sources

Previous studies using the CMIP5 data have estimated that average temperature over East Africa will increase by 2-3°C by mid-century, and 2-5°C by end-of-century depending on medium to high emission scenarios and the range of estimates of different models (Otieno et al., 2013, Rowell et al., 2016, Ongoma et al., 2018). Temperature rise is shown not to be uniform across East Africa, with additional factors, such as proximity to the ocean, affecting the size of temperature rise. On average the models show an increase in rainfall, particularly from October to February (Otieno and Anyah, 2013, Ongoma et al., 2018). However, there is a broad spread of estimates from models, with some showing a decrease in rainfall (Rowell et al., 2015). The possible changes to extreme events have been studied with CMIP5 (Ongomaet al., 2017). Though there may be less confidence in some extreme metrics with CMIP5 data, they can still provide some useful indications which can be explored in more detail with other data. Ongoma et al. (2017) find that there could be around 50% more warm nights by end-of-century for a medium emission scenario (RCP4.5), and that it is coastal regions where warm nights are likely to increase most. Furthermore, they find increases in the number of very wet and extremely wet days, as well as increase in the 1-day and 5-day maximum rainfall.

HyCRISTAL has undertaken a much more detailed evaluation of the aspects of climate change, as represented by CMIP5-RCP8.5, for metrics of interest to stakeholders in East Africa (Bornemann et al., 2019). Figure 1 gives an example of how this analysis is presented in order to provide a sense of the uncertainty in the estimates. It shows a lower and higher estimate of change. For instance over the horn of Africa, models show possible futures between no change to increases of up to around 2mm in October-December rainfall, i.e. a decrease in rainfall in this region and season is unlikely. Whereas for Southern Tanzania, the models show a decrease of around 1mm to no change. So an increase in rainfall in this region is unlikely. This information is available for a wide range of metrics (Bornemann et al., 2019)

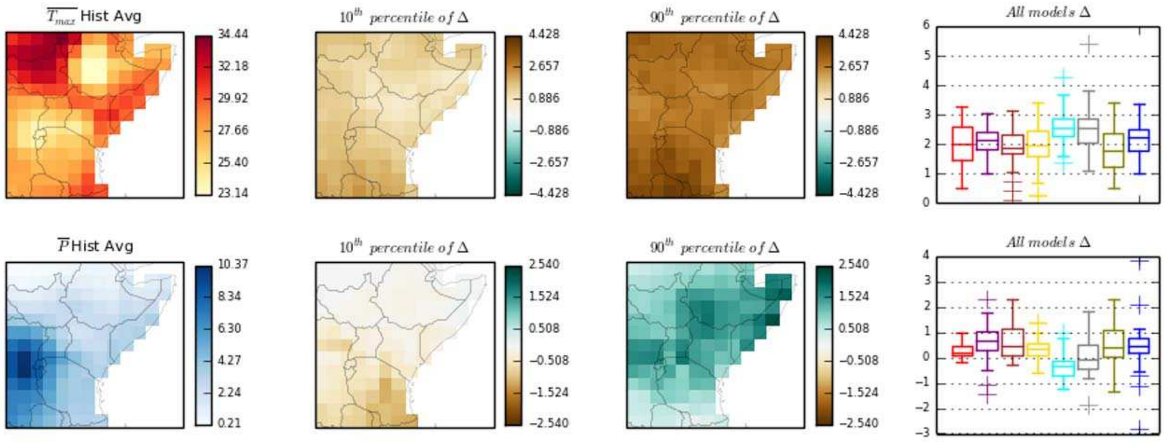

Figure 1. Sample of geographical plots for exemplar metrics (October-December, 2040-2059 horizon). Column 1 shows the CMIP5 models' historic average. Columns 2 and 3 map the projection uncertainty by ranking the change from all contributing models at each gridbox, and plotting the 10th and 90th percentiles of this distribution across models, i.e. the 10th and 90th percentiles in model space. Column 4 shows box-and-whisker plots of projected change across all models at 8 representative locations providing a further perspective on uncertainty (these are: northern South Sudan, northern Uganda, southern Ethiopian Highlands, Kenyan Highlands, Lake Victoria, eastern Congo Basin, Tanzania plateau, and Tanzania lowlands). Different metrics are shown in each row: Top is shown monthly mean of daily max temperature (°C), bottom is shown monthly mean precipitation (mm/day).

An additional breakthrough made under HyCRISTAL, is that the range of model estimates of total rainfall during the Long Rains has been reduced by a third, by constraining model estimates using the observed sensitivity of clouds over the southern Indian Ocean (Rowell and Chadwick, 2018; Rowell, 2019). This came from our approach of first understanding why different models produce different projections – a pair of extreme models was found to have exceptionally strong cloud-ocean feedbacks over the southern Indian Ocean – and then using this information to appropriately evaluate the models against observations.

The rainy seasons of East Africa

The onset, cessation, length and total rainfall during the two East African rainy seasons is of great importance to countries in the region. A number of pieces of research have investigated our ability to forecast each rainy season at a lead time of a few weeks or months. Walker et al. (2019) has shown the challenge in forecasting the long rains compared to short rains, but new insights have been recently gained which identify drivers of long rains variability and can improve seasonal forecasts (Vellinga and Milton, 2018). Developments have also been made in our understanding of model biases, with moisture flow from the Indian Ocean shown to be important in both the short rains (Hirons and Turner, 2018) and long rains (Sabiiti et al, *in prep.*).

In recent decades there has been a well-documented decline in the long rains (and given the projected rainfall increase of many climate models, this is sometimes referred to as the Eastern Africa Rainfall Paradox). Wainwright et al. (2019) shows the recent rainfall decline is linked to a shorter season, with a later onset and earlier cessation. Over the same period, the strength of the Arabian Heat Low increased, and the strength of the Somali Jet increased. This is associated with the earlier cessation of the Long Rains. Changes in sea surface temperature gradients in the Indian Ocean are also linked to changes in onset and cessation. Overall this work has greatly developed our understanding of drivers of recent climate variability.

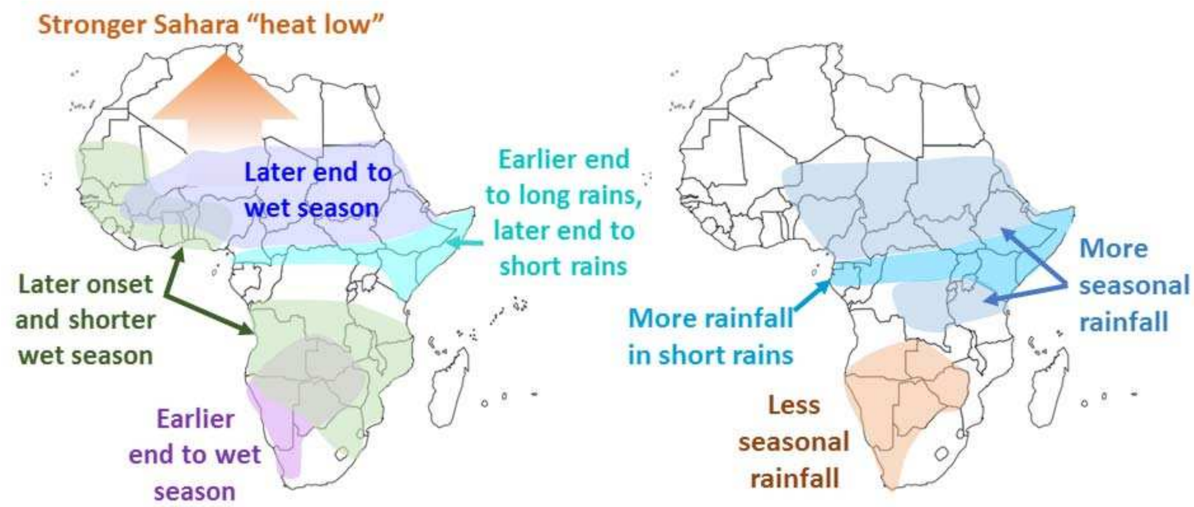

Figure 2. Schematic showing changes in timing of the wet season (left) and changes in seasonal rainfall totals (right) for end-of-century under a business-as-usual scenario (RCP8.5).

There have only been a few studies to date describing how future climate change could affect the timing of the rainy seasons (Cook and Vizy, 2012, Dunning et al., 2018). These studies have given some useful indications of potential changes, as well as the drivers of change, in East Africa's rainfall seasons. Notably, a summary from Dunning et al. (2018) of Africa-wide changes are given in figure 2. For East Africa, they are earlier cessation of the long rains, later cessation of the short rains, and more rainfall during the short rains: although variations between models means that the sign of change in both seasons remains uncertain. However, the different responses over other parts of Africa highlight the need for the East Africa focus that HyCRISTAL has provided.

Day-to-day and year-to-year variability of rainfall

Investigation into the processes that drive variability in today's climate develops the understanding needed to provide confident projections of the effects of climate change. Recent work has shown that improved representation of convection in a weather model provides useful skill in forecasting East African rainfall on sub-daily timescales (Woodhams et al., 2018), and this model has been used to demonstrate complex characteristics of the initiation and propagation of storms over the Lake Victoria Basin (Woodhams et al., 2019). Benefits of such a model have also been seen for longer climate time-scales by Finney et al. (2019a), who showed better timing of rainfall, closer to the afternoon peak of rainfall seen in many parts of East Africa.

Meanwhile, Jackson et al. (2019) and Finney et al. (2019b) have studied various atmospheric features that control rainfall variability. Certain large-scale waves in the atmosphere (similar to waves in water) can enhance or suppress rainfall. Jackson et al. (2019) show that roughly 15% of day-to-day variability in rainfall over East Africa as a whole can be explained by these waves, known as Kelvin waves. Other atmospheric oscillations, such as the Madden-Julian Oscillation (MJO), are also known to influence East African rainfall. Finney et al. (2019b) has shown how the MJO and the presence of tropical cyclones in the Indian Ocean can lead to moisture flow from the Congo to East Africa and enhance rainfall in the region. This is an important feature since climate change can impact atmospheric flows.

Whether floods are experienced during rainfall significantly depends on the saturation level of the ground. Anyah et al. (2019) have been working to improve the simulation of water flow into the ground, and found that these improvements allow more consistent representation of flooding conditions in wet and dry years over East Africa. Knowledge from this work can feed through into our understanding of flooding events in weather forecasting and under climate change.

<u>**Extending our understanding of future extremes with further climate model experiments**</u>

CMIP5 data provide a huge breadth of information regarding climate change, they are especially useful in projecting future temperatures and total rainfall changes. But their usefulness in projecting changes in particular features of climate, such as extreme rainfall events and dry spells, are known to be limited, due to the coarse model grids used. Therefore, in order to assist decision-makers in East Africa who require information on such extreme weather events, HyCRISTAL is using an enhanced climate model (called CP4) to add depth to our understanding of plausible changes in climate. This model is much higher resolution than CMIP5 models, and therefore can more realistically simulate features such as lakes or smaller-scale processes such as the convective storms that generate rain.

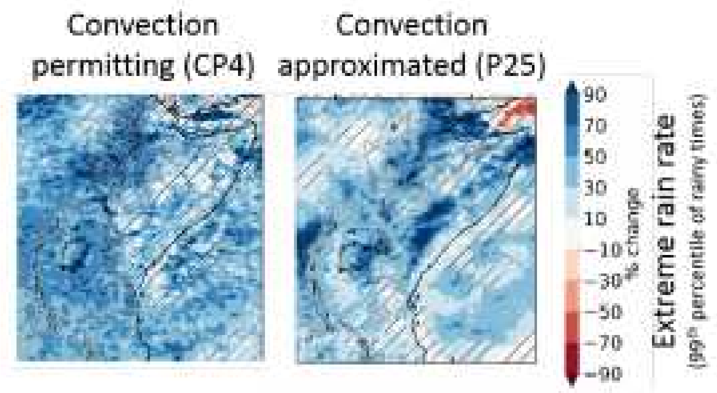

Figure 3. Changes in the 99th percentile of rainy 3 hour periods for CP4 (convection-permitting) and P25 (convection parametrised) by end-of-century under a high-end, business-as-usual scenario (RCP8.5). Rainy times are when 3-hourly rainfall exceeds 0.125mm. Hatching shows insignificant grid cells at 5% level. Grey contours show 1000m/2000m orography.

An Africa-wide study of a simulation of future climate with the CP4 model shows East Africa to be different to many other parts of Africa for several aspects of climate change (Kendon et al., 2019). Notably, for this study, rainfall during the main rainy season (for a given location in East Africa) occurs more frequently under climate change. Kendon et al. (2019) shows that there could be an increase in rainfall from intense events with less coming from lighter rainfall events. An additional study of this data has been made by Finney et al. (2019c), and focuses specifically on East Africa. This study has found that future changes to the sea breeze could mean that coastal cities such as Mombasa may not see the same rainfall increases projected for locations further inland. Finney et al. (2019c) also looks more closely at the changes in extreme rainfall over East Africa (Figure 3). Results suggest that, unlike projections from a CMIP-like (P25) model, extreme rain rate increases in this scenario are widespread across East Africa (~50%). The CMIP-like model shows more spatial variability in its projections, but we believe this is due to physical limitations of the model. Therefore the enhanced, high-resolution, simulation provides important new information regarding rainfall extremes under climate change.

Another limitation of CMIP5 is that the RCP scenarios do not sufficiently explore the range of plausible air quality policies and their remote influences. Scannell et al. (2019) examine additional experiments to show that more aggressive aerosol emission cuts in regions remote from East Africa could delay both the onset and withdrawal of the Short Rains. This motivates the need for wider exploration of air quality scenarios to assess the robustness of these changes and further inform climate adaptation in Africa. Revised estimates of emission impacts of legislated measures every 5-10 years would also aid near term climate adaptation information for African stakeholders.

Linking to HyCRISTAL impacts and decision-making research

Whilst this summary has looked to share the developments in climate science undertaken in HyCRISTAL, another key component of the HyCRISTAL project has been to work with stakeholders to understand the implications of climate science for their decision-making. Below is information regarding where you can find more information on HyCRISTAL's work with stakeholders.

Communication: Climate Risk Narratives *David Rowell* *dave.rowell@metoffice.gov.uk*

To reduce the complex multi-dimensional nature of climate model projection data, HyCRISTAL has developed three plausible quasi-quantitative climate scenarios. This concept of 'Climate Risk Narratives' (CRNs) (Jack et al. 2019) has been developed to communicate potential climate change and impacts to audiences with different levels of climate science capacity (Burgin et al. 2019a,b). These CRNs are now being used both in engagement with HyCRISTAL stakeholders and to help extend the remit of the Greater Horn of Africa Climate Outlook Forum (GHACOF) to longer term climate change in addition to its traditional focus on seasonal timescales.

https://futureclimateafrica.org/resource/possible-futures-for-urban-east-africa-under-a-changing-climate/

https://futureclimateafrica.org/resource/possible-futures-for-urban-east-africa-under-a-changing-climate-2/

https://futureclimateafrica.org/resource/possible-futures-for-rural-east-africa-under-a-changing-climate/

https://futureclimateafrica.org/resource/possible-futures-for-rural-east-africa-under-a-changing-climate-2/

Urban Water, Sanitation and Hygiene (WASH). *Barbara Evans* *B.E.Evans@leeds.ac.uk*

In the urban WASH pilot we are integrating information about current effects of weather (primarily flooding), existing inventories of systems for human excreta management (sanitation) and stormwater management (drainage) available and their management, with a range of qualitative information about how flooding impacts on household and neighbourhood behaviours and health outcomes. The purpose of this collation of information is to enable local technical and political decision makers to interrogate the current and likely future social and health impacts of climate on existing weak infrastructure systems. As well as developing tools for decision-makers we use the HyCRISTAL Climate Narratives to explore how these impacts are likely to worsen in the future. The platform can also be used to explore the relative benefits of a wider range of interventions than those which are usually tabled. So for example demonstrating the relative impacts of improved operations and maintenance on future climate resilience. At the same time, we can demonstrate that likely future mitigation effects of such interventions, providing a suite of information to support more effective decision making.

Rural Livelihoods. *Ros Cornforth* *r.j.cornforth@reading.ac.uk*

HyCRISTAL's rural pilot thematic study was established in two Lake Victoria administrative units—Mukono District in Uganda and Homa Bay County in Kenya. A multi-stakeholder engagement approach and mixed-method research design was developed by the HyCRISTAL rural thematic team.

Each element played a contributing part in developing an understanding of context and communication pathways in the region. This multidimensional approach to rural adaptation has involves a range of interdependent studies and activities, which combine to contribute to the development of a knowledge ecosystem that will continue to engage with both long-term climate projections provided through HyCRISTAL climate modelling, and reliable context-specific information provided through a rich suite of social science data collection methods and engagement activities such as the Household Economy Approach (HEA), the Individual Household Method (IHM), participatory market systems development (PMSD), participatory communications and visual methods research, advocacy work, and ethnography. Meanwhile, the innovative IDAPS (Integrated Database for African Policymakers) platform provides an opportunity for decision makers to take actions based on understanding derived from that knowledge ecosystem. The convergence of various strands of research and communication—from local to national to regional—is being used to enable policymakers to make informed short- and long-term decisions related to rural adaptation and, specifically, the problem of under-investment in the rural economy and rural populations. Short-term decisions cover a period of 1 to 3 years, such as programs to mitigate extreme events, while long-term decisions cover 5 to 40 years and might include the provision of major infrastructure like roads, irrigation schemes, and institution-based training programmes. Furthermore, the rural thematic studies have highlighted the need to critically interrogate the implications of 'adaptation' and 'resilience' as policy responses to climate change in poorer rural communities. It is clear from the empirical studies that climate resilience cannot be de-linked from investment in sustainable (green) economic development with a strategic focus on the needs and aspirations of the growing numbers of largely neglected youth.

Hydrological modelling of river basins. *Dan Lapworth djla@bgs.ac.uk*

Adaptation to climate change in the water supply sector requires a detailed understanding of future projections in water resource availability. Unfortunately, climate change impact studies in African regions are often hindered by the extent in variability in future rainfall prediction. To help address this limitation, "scenario-neutral" methods have been developed which stress a hydrological system using a wide range of climate futures to build a "climate response surface". Following detailed discussions with the Ugandan MWE we initially developed a hydrological model (using the lumped catchment model GR4J) and scenario-neutral framework to quantify climate change impacts on river flows in the Katonga catchment, Uganda. Using a delta change approach, we then systematically changed rainfall and potential evapotranspiration inputs to develop response surfaces for key metrics, developed with Ugandan water resources planners (e.g. Q5, Q95). This approach was then built on to assess the impacts of changes in future climate to environmental flows across the Lake Victoria Basin. Implications of future climate in East Africa for water resources management and climate change adaptation in the region, such as surface water abstractions, hydropower and environmental flows, are assessed in the context of national water management planning horizons. This work is ongoing and peer reviewed papers are in preparation.

Plausible future Lake Victoria lake levels. *John Marsham j.marsham@leeds.ac.uk*

The HyCristal Transport Pilot Project (HyTPP) was funded by the UK Department for International Development (DFID), through the Corridors for Growth Trust Fund administered by the World Bank. HyTpp was motivated by the need to ensure that investment in transport infrastructure around the Lake was informed by possible future changes in lake levels. In addition, Lake Victoria is a source of the Nile and hydropower. With climate change we expect a change in lake levels, as the regional climate becomes either wetter or drier. HyTPP derived a plausible range of future lake levels and produced a report for the World Bank and its partners, with a peer-reviewed paper in preparation.

Climate Information for Tea (CI4Tea). *Neha Mittal* n.mittal@leeds.ac.uk

CI4Tea, a joint project of HyCRISTAL and UMFULA, has produced tailored climate information for the tea sector in Kenya and Malawi by iteratively engaging various tea supply chain actors including tea estates, smallholder farmers, and tea research institutes. Communication of site-scale climate information for tea-specific metrics at decision relevant future time horizons and associated uncertainty enable the stakeholder understanding of the likely impact of future climate change on tea yield and its quality, and priortisation of local management and adaptation options. Climate briefs for dissemination to in-country stakeholders and tea sourcing companies in the UK, and a peer-review paper are under preparation.

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