FCFA IMPALA

Report of 3rd IMPALA science meeting

12-13 December 2017, University of Reading

(covering the period Feb. 17 to Dec. 17)

Third IMPALA Science Meeting, University of Reading, 12-13 December 2017

Contents

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Executive summary

The overarching aim of IMPALA (Improving Model Processes for African cLimAte) is to deliver a step change in global model climate prediction for Africa on the 5-40 year timescale by delivering reductions in model systematic errors, resulting in reduced uncertainty in predictions of African climate and enabling improved assessment of the robustness of multi-model projections for the continent. The project commenced in February 2015. This report documents progress as reported at the third IMPALA science meeting 12-13 December 2017 and covers work over the year since the second Science Meeting (19-20 January 2017)[1].

IMPALA focuses model improvement on a single multi-temporal, multi-spatial resolution model, the Met Office Unified Model (MetUM), to allow rapid pull through of improvements made in the project into improved African climate modelling capability. This focus aids rapid progress which may then be exploited by the wider modelling community – since the methodologies developed and understanding obtained can potentially be applied to a wide range of contemporary climate models.

Good progress has been made across IMPALA's four work packages. Brief highlights include the following. The high-resolution (4.5km) convection-permitting pan-African regional model (CP4-Africa) simulations have been extended with a full set of 10 years of present-day simulations (1997-2006) and 5 years of idealised future simulations (representative of 2100) now completed. A cross-Regional Consortia questionnaire finds that all consortia are using the simulations for regional climate research and/or in plans to integrate the outputs into climate change advice for decision-makers across a range of sectors. New studies with the simulations continue to show step-change improvements in simulation of African climate. As well as improved season-mean rainfall, benefits include more realism in representation of the following: westward propagating systems; extreme, short-lived rainfall events; interactions with the vegetation canopy; and the diurnal cycle of rainfall. CP4-Africa simulations of heatwave frequency and intensity have also been characterised. The CP4-Africa idealised future simulations, representative of 2100, are providing the first evidence on how these improvements will modify and strengthen our understanding of future climate change - leading to more robust products and tools for decision-makers.

IMPALA studies on model representation of local and remote drivers of African climate have been published and are providing important guidance priorities for Africa-focused climate model development. Notably, a new convection scheme that results in a more realistic storm cell development and clustering as well as improved African Easterly Waves and diurnal rainfall cycle has now been implemented in the latest global MetUM version.

Four IMPALA Africa-based core researchers have remained active in regional evaluation studies of MetUM performance – a major achievement being co-authorship of the now published BAMS paper "Evaluating Climate Models with an African Lens". All four core researchers have now engaged Early Career Researchers (ECRs) (a total of 6 across the regions addressed) who are working on new aspects of model evaluation. Two core Africa-based researchers have been distinguished by appointment as lead authors on IPCC AR6 WG 1 Chapter 4 and Chapter 8.

Project meetings

The IMPALA project management committee has continued to guide the project through email communication and via meetings of groups with common membership such as the WG on CP4-Africa, the FCFA mid-term conference and the 3rd IMPALA Science Meeting. No formal meeting of the management committee took place this year.

[1] http://www.futureclimateafrica.org/wp-content/uploads/2015/10/impala_2nd_science_meeting_report_f.pdf

IMPALA has engaged with CCKE on a number of activities including: organisation and delivery of the FCFA mid-term conference 4-8 September 2017, Cape Town, South Africa; contributions to the CCKE quarterly newsletters; utilisation of the FCFA Mobility and Innovation Funds (IMPALA now has 6 ECRs); press release for the BAMS paper "Evaluating Climate Models with an African Lens"; the NERC Biannual Achievements Reports and the DFID annual review of FCFA; and with contributions to the FCFA website. Rachel James (WP3 – University of Oxford) prepared and delivered a webinar entitled: "How can climate models be improved over Africa? Investigating global models with local knowledge" .

The FCFA mid-term conference included two IMPALA led side meetings/break out groups: a WP3 meeting on model evaluation led by Rachel James at which the concept of an African model evaluation hub was advanced with discussion of ideas on how to initiate it (see Section 4.3); and a parallel climate science session on "CP4-Africa and CMIP model data: analysis and use".

There have been three meetings of the MetUM Africa Process Evaluation Group (PEG), 27 April 2017 19 October 2017 and 26 April 2018, 18 March 2016. These meetings have included regular updates on CP4-Africa output and other IMPALA results as well as results from all four Regional Research Consortia. All presentations are available on the collaboration twiki pages at: http://collab.metoffice.gov.uk/twiki/bin/view/Development/AfricaPEG. The cross-FCFA Working Group on the CP4-Africa model has met three times since January 2017 and remains active to monitor output, discuss technical issues arising during the runs, and to facilitate dissemination to the RCs.

An IMPALA science meeting was held at the University of Reading, 12-13 December 2017 and is the subject of this report. The meeting was attended by around 30 scientists engaged in the project and included representatives from all 4 Regional Consortia. The 4 IMPALA Africa-based partners also presented and participated, three by video link and one in person. The meeting included a discussion session to scope the IMPALA-led cross-FCFA outputs identified at the Cape Town mid-term meeting, namely a BAMS-style paper on CP4-Africa and technical guidance material for accessing and processing CP4-Africa outputs.

Papers (submitted/published), internal project reports

Seven peer-reviewed papers have been published this period, making a total of 11 since the project start, with a further 2 papers accepted/submitted for publication and several more in preparation. Specifically, peer-reviewed publications are:

Hawcroft et al. 2018: The contrasting climate response to tropical and extratropical energy perturbations. Climate Dynamics.
Vellinga et al. 2018: Drivers of interannual variability of the East African 'Long Rains'. Quarterly Journal of the Royal Meteorological Society.
Tomassini et al. 2017: The interaction between moist diabatic processes and the atmospheric circulation in African Easterly Wave propagation. Quarterly Journal of the Royal Meteorological Society.
Stratton et al. 2018: A pan-Africa convection-permitting regional climate simulation with the Met Office Unified Model: CP4-Africa. Journal of Climate.
Jones A et al. 2017: Impacts of hemispheric solar geoengineering on tropical cyclone frequency. Nature Communications.
James et al. 2017: Evaluating climate models with an African lens. Bulletin of the American Meteorological Society.
Hirons and Turner, 2018: The impact of Indian Ocean mean-state biases in climate models on the representation of the East African short rains. Journal of Climate

Near submission or in review
Kendon et al.: Enhanced future changes in wet and dry extremes over Africa at convection permitting scale. Nature Climate Change.
Finney et al: Implications of improved representation of convection for the East Africa water budget using a convection-permitting model

Progress highlights
Progress highlights are summarised below by work package.

WP1: Influence of large-scale modes and teleconnections on African climate:

- Understanding of the strong linkage between errors in the MetUM's relative albedo between the hemispheres and errors in tropical rainfall has been further advanced with two further papers published making five in total on this area of research. The albedo errors are linked with errors in cross-equatorial energy transport and biases in the location of the ITCZ circum-tropical rainband as well as its erroneous double-structure - and consequently of high importance to Africa. Improved understanding of these hemispheric scale constraints on tropical rainfall are crucial to improved modelling. Errors are present in all state-of-the-art models and are one reason why most models fail to achieve good simulation of the northern monsoons. The research direction is now focused on understanding the sensitivities of these errors to model parameters and formulations through a perturbed physics ensemble of the MetUM as well as a multi-centre model intercomparison project (MIP) led by an IMPALA researcher.
- A technique for understanding errors in model climate is being developed which exploits the known similarity in the characteristic biases of long-term simulations with those of short-term prediction (first 5-day forecasts). This analysis has revealed a fast-growing potential source of error is over-developed tropical continent heat lows, primarily over South America and Africa, likely due to errors in cloud distribution and erroneous heating of the land surface. The erroneous circulations set up by these heat low errors may contribute to errors in the Africa Easterly Jet.
- Further nudging experiments to investigate the remote versus local forcing of model systematic errors over Africa have been developed and a large number of potential remote source regions for forcing of African model errors have been investigated in 20-year AMIP simulations. The adjacent South Asian summer monsoon region remains one of the key driving regions for errors in the mean state of upper-tropospheric winds over Africa (tropical easterly jet (TEJ) at 200hPa). This points to a need to improve the wider Asian Summer Monsoon circulation biases, and developments implemented to the UM convection scheme at proto-GA8/GC4 (convective memory) and planned for GA9/GC5 (scale aware convection scheme – COMORPH) are targeted at addressing such biases. Surprisingly, in these long-term climate simulations, correcting the large errors seen in divergent flow over South America have only a small influence on the African circulation (TEJ and AEJ) biases.
- Significant progress has been made in increasing understanding of the drivers of interannual variability in both the East Africa Short and Long rains seasons (EASR, EALR) and in characterising model performance, with two published papers. In addition, insights have been gained into reasons for the striking difference in the large-scale drivers of the two seasons: the EASR is strongly linked to tropical SST variability, whereas the EALR shows very little such connection. For the EASR an analysis of the CMIP5 ensemble has shown that errors in the model mean state over the Indian Ocean have a primary influence on models' ability to correctly simulate the variability of westerly moisture transport into EA related to variability in the Indian Ocean Dipole (IOD). Models that correctly simulate a mean-state westerly equatorial low-level flow have better simulations of moisture transport into the region and EASR variability relative to models with an (erroneous) easterly mean

state. Coupled models appear more prone to an erroneous easterly mean-state. These results highlight the importance for Africa of a renewed focus on improving modelling of Indian Ocean-related Africa variability to "catch up" with the focus to-date on simulating ENSO and its impacts and are providing pointers to model development. For the EALR season, research has shown that this season is characterised by large-scale subsidence in the upper atmosphere, and interannual variability in rainfall is mainly influenced by drivers that can diminish/enhance this subsidence (generating wetter/dryer than average seasons respectively). The Madden-Julian Oscillation, the Quasi-Biennial Oscillation and SST in the Arabian Sea are identified as primary drivers. As for the EASR – these findings are informing directions for model improvement. There is evidence that the convection scheme improvements implemented in proto-GA8/GC4 have improved representation of MJO links to the region.

- A further focus has been on analysing MetUM simulations of the West African monsoon and its sensitivity to model resolution and ocean-atmosphere coupling. Studies have been extended to the latest MetUM versions (GA7/GC3) with findings to date revealing an erroneous double structure to the main region of ascent in coupled simulations as well as a decoupling of the ascent region with the location of peak rainfall.

WP2: Improved representation of local processes: convection, land surface, aerosol

- *Convection (1)*: Representation of tropical convection is a major weakness in climate models and research to improve this has continued. Work reported last year on significant improvements to the convection scheme has begun to pull through to the operational MetUM. In particular the prognostic convective entrainment improvement has now been implemented in MetUM version proto-GA8/GC4. This modification generates a more realistic, slower build up of convective storms and improves the modelled peak in the diurnal cycle – reducing the tendency for the peak to occur too early in the day in the tropics. The new scheme also improves representation of African Easterly Waves.
- *Convection (2)*: Work on a new scale-aware convection scheme for the MetUM has continued. A scale-aware scheme is needed because the MetUM has configurations at a wide range of resolutions – from 100s of kilometres in traditional climate models to e.g. 4.5km in the CP4-Africa model. The convection scheme should be capable of responding correctly at different resolutions such that the resolved and unresolved processes are realistically partitioned at all resolutions. Research has suggested a number of new design features for the scheme. For example, that the closure assumptions of a scale-aware scheme are more appropriately based on mass flux at the cloud base rather than the current schemes' use of convective available potential energy (CAPE). Coding of a new scheme is in progress and testing for inclusion in MetUM version GA9 (December 2018) is underway.
- *Land model development*: The aim of this work, which uses the Joint UK Land-Environment Scheme (JULES), is to develop better simulations of vegetation anomalies that are related to rainfall variations – permitting a better representation of vegetation-climate feedbacks critical for African climate. To this end the sensitivity of vegetation phenology (e.g. start of season, peak of season) to JULES parameters is being studied – particularly those related to the drought-deciduous response. Findings so far include that in some locations the timing and magnitude of the modelled leaf area index (LAI) are improved by linking leaf turnover rate (the rate at which leaves are produced, senesce and fall) with moisture availability. This has been noted to improve simulation of the minimum in LAI in southern African grasslands over the July-August period. Further analysis on surface water budgets has been completed using the JULES implementation in CP4-Africa (see also below). The fraction of rain days per season is much improved in CP4-Africa: reducing from rain nearly every day (in season) in the parameterised convection model to on average 1 day in 3 in CP4-Africa. Consequently, the overestimation of canopy

interception is also improved: 10-40% of annual rainfall is intercepted at the canopy in the parameterised convection model compared to observed losses of order 10%. However, CP4-Africa appears to slightly underestimate canopy interception – having values less generally than 10%.

- *CP4-Africa model simulations and analysis*: The design and successful testing of the convection permitting 4.5km pan-Africa simulation, CP4-Africa, and the “control” non-convection permitting 25km regional model (nCP25-Africa) have been described in previous reporting. A major milestone was reached this period with the completion (November 2017) of the planned 10 years of present-day (1997-2006) CP4-Africa simulations. Idealised CP4-Africa simulations of future climate, representative of 2100, have now completed 7 years. IMPALA has made the CP4-Africa and nCP25-Africa simulations widely available to the FCFA Regional Research Consortia (RRCs) via the JASMIN facility. Analysis and comparison of both present-day and future idealised simulations is underway within IMPALA and the RCs and pioneering science is now pulling through with several papers close to publication.

  Present day simulations: Ten-year seasonal means have been created from the simulation and compared with the same 10 years nCP25-Africa and the driving global model - both running with convective parametrization. Overall, the findings are similar to an earlier comparison using five-year means that has been published this period in Stratton el al. 2018, and to results reported last year with 3 years and 2 months of simulations. The simulations indicate substantial improvement in CP4-Africa JJA average rainfall over that of the nCP25-Africa and global models. This is true across most parts of the African continent with, most notably, a reduced dry bias over the Sahel and associated reduction in radiative biases due to the presence of brighter, more organised clouds. Encouragingly, results suggest that the variability and spatio-temporal characteristics of the rainfall all appear to be better represented in the CP4-Africa model. There is evidence of better capture of westward propagating convective systems and a better intensity/frequency distribution of 3-hourly precipitation events. The diurnal cycle of convective precipitation over land is also better handled in CP4-Africa. Over the stratocumulus region to the west of Africa, particularly where cloud-aerosol interactions are important, both CP4-Africa an nCP25-Africa perform rather worse than the global model, at least partly due to the simplified representation of aerosols in these regional models.

  New analysis this year includes: Analysis of CP4-Africa rainfall and vertical motion in the main rain band over central Africa throughout the seasonal cycle shows more intense precipitation and increased ascent within the rain band throughout year relative to nCP25-Africa. Analysis of 3-hourly rainfall and vertical motion shows that vertical motion is more strongly coupled to precipitation in CP4-Africa with much greater increase in ascent during rain episodes. North and south of the rain band, CP4-Africa has less precipitation and more descending motion than nCP25-Africa. These differences are most marked in the February-March period. Additionally, a pan-African analysis of heatwaves has found that CP4-Africa has more heatwaves than nCP25-Africa and the mean magnitude of heatwaves is higher, particularly over the Congo basin.

  Future idealised simulations: the CP4-AfricA future simulation has completed 5 years to date. Analysis of these runs, indicates that future increases in extreme 3-hourly (and to a lesser extent daily) precipitation are greater in CP4-Africa compared to the nCP25-Africa regional model. Also, at the same time, we see a greater tendency for a lengthening of dry spells during the wet season in CP4-Africa. These results give a first insight into how the improved representation of convection in CP4-Africa impacts on projections of future climate change across Africa.

Regional Research Consortia (RRC) studies using CP4-Africa
Highlight results from analysis of CP4-Africa simulations by the FCFA RRCs include the following:

AMMA2050: CP4-Africa shows…
- a reduced dry bias in the Sahel seasonal totals and reduced bias in rainday frequency (much fewer rain days in CP4-Africa – though higher totals).
- reduced (improved) canopy interception of rainfall due to heavier rain episodes with increased (sub-surface) run off.

HyCRISTAL: CP4-Africa shows…
- improved propagation of storm cells in the Lake Victoria region of East Africa;
- improved timing of the EASR season through changed moisture budget;
- plausible representations of mesoscale land/mountain/lake breezes and convergence over Lake Victoria with more lake convergence overnight and in the early morning – opening up potential to study the impact of climate change on these features using the future idealised simulations.

UMFULA: CP4-Africa shows…
- a much-improved simulation of the seasonal cycle of Tropical Temperate Cloud Bands (TTCBs) – a major rain bringing system to southern Africa (the nCP25-Africa and global models have too many TTCBs in southern winter).

WP3: Metrics and Model Evaluation

- Reviews and final revisions of a manuscript submitted last year has resulted in publication of a position paper promoting a framework on model evaluation for Africa, with examples of evaluation of the MetUM – prepared with the IMPALA Africa-based partners. The paper is published online in the Bulletin of the American Meteorological Society (BAMS): James et al: “Evaluating Climate Models with an African Lens”. Additionally, 6 ECRs have been recruited to work with Africa-based partners on model evaluation over East, West, Central and southern Africa, including through use of the FCFA innovation fund.
- Further model evaluations have continued and include analysis of the MetUM climatology and representation of drought over West Africa; analysis of the model representation of circulation dynamics associated with TTCBs over southern Africa; analysis of the reasons for the MetUM’s wet bias over eastern Central Africa and its links to vertical velocity associated with transverse circulations driven by southern and northern branches of the African Easterly Jet; further analysis of MetUM rainfall, vertically integrated moisture and circulation biases for the East Africa SR and LR seasons and case study analysis of both seasons for 1997 and 2011.
- An initiative to link with other international activities (e.g. the CMIP Metrics Panel) to foster a model evaluation hub for Africa (providing e.g. a repository of metrics and code) has been further advanced at a breakout group at the Cape Town mid-term FCFA conference. Letters introducing this initiative are now being sent to a wide range of experts in African climate modelling (including the CORDEX community).

WP4: Integration and characterisation of model improvements and implication for future climate change

- The prognostic convective entrainment improvement to the MetUM convection scheme has been pulled through into version proto-GA8/GC4 and further convection improvements (e.g. scale awareness) are undergoing tests for GA9/GC5.
- Work on the implications of model improvements on assessment of climate change signals is linked with WP2 and has been reported there. Note in particular that CP4-Africa indicates that future increases in extreme 3-hourly (and to a lesser extent daily) precipitation are greater than in the conventional (i.e. CORDEX type) nCP25-Africa regional model. Also, at the same time, we see a greater tendency for a lengthening of dry spells during the wet season in CP4-Africa.
- An in-depth case of MetUM representation of African Easterly Waves (AEWs) including use of a new diagnostic tool based on potential vorticity tracking has been published in the peer reviewed literature (Tomassini et al 2017). The investigation provides insights into priorities for model development and gives special focus to the coupling of dynamical aspects of the wave and moist convection. The relation between baroclinic features of the wave and latent heating is explored. Latent heating at and slightly ahead of the wave trough is found to reinforce and sustain the anomalous wave circulation through potential vorticity (PV) generation and vortex stretching.

Progress with CP4-Africa simulations

In previous reports delays with the processing of the CP4-Africa simulations were noted – this was due to slower than anticipated processing on the HPC system (a circumstance beyond IMPALA's control). There have been no further delays this year. The CP4-Africa present-day climate runs are now complete and in use by Regional Consortia. The idealised future simulations have completed 7 years – these are available to Consortia and are sufficient to begin analysis. A full 10 years of future simulations is expected to become available by October 2018.

1. Introduction

The overarching aim of IMPALA (Improving Model Processes for African cLimAte) is to deliver a step change in global model climate prediction for Africa on the 5-40 year timescale by delivering reductions in model systematic errors, resulting in reduced uncertainty in predictions of African climate and enabling improved assessment of the robustness of multi-model projections for the continent. The project commenced in February 2015. This report documents progress as reported at the third IMPALA science meeting 12-13 December 2017 and covers work over the year since the second Science Meeting (19-20 January 2017).

IMPALA focuses model improvement on a single multi-temporal, multi-spatial resolution model, the Met Office Unified Model (MetUM), to allow rapid pull through of improvements made in the project into improved African climate modelling capability. This focus aids rapid progress which may then be exploited by the wider modelling community – since the methodology developed and understanding obtained is widely applicable across all contemporary climate models.

Research is structured in four Work Packages (WPs):

WP1: Influence of large-scale modes and teleconnections on African climate
Large-scale modes of variability with centres of action remote from Africa have a major influence on African climate through signals transmitted to the continent along "teleconnection pathways". WP1 tasks are designed to improve understanding of the mechanisms associated with these modes and pathways, evaluate their representation in the MetUM and develop strategies for their improved representation.

WP2: Improved representation of local processes
Local processes associated with tropical convection, land-atmosphere coupling and aerosol loading play a major role in driving African climate variability both directly and indirectly through influences on the large-scale dynamics. WP2 tasks are focussed on developing better understanding of these processes and designing improved model representations (parameterisations).

WP3: Metrics and Model Evaluation
This activity is coordinating and undertaking model evaluation by identifying, reviewing and prioritising pan-Africa metrics focused on process-based analysis and indices with impacts relevance. Partnerships with African-based experts on model performance are active and are focusing on defined regions West, East, Central and southern Africa. The performance of the "baseline" MetUM (GA6/GC2 – the consolidated MetUM version at the start of IMPALA) over Africa has been evaluated. The improvement in performance following WP1 and WP2 science will be measured in Year 4 of the project.

WP4: Integration and Characterisation of model improvements and implication for future climate change
This activity integrates advances in model development and improvement from WP1 and WP2 – pulling through the advances into improved model prediction capability. There is strong gearing with ongoing global model development at the Met Office, which follows an annual development cycle and with the Africa Process Evaluation Group (PEG) which monitors the impact of model developments on performance for Africa and prioritises model developments for integration into the model. The activity is characterising the impact of model improvements on the trustworthiness of model processes driving the future climate change signal for sub-Saharan Africa on the 5-40 year timescale. This includes assessment of the role of convection-permitting resolution on the main processes (from the CP4-Africa and other high-resolution simulations).

2. Management, project meetings and interaction with CCKE

The IMPALA project management committee met informally as an adjunct to meetings of the Working Group on CP4-Africa meetings (the PI and WP leaders are members of both the committee and the WG) in January, May and November 2017 as well as at the IMPALA science meeting on 12-13 December 2017. This has proved sufficient to maintain internal steering to the project science and to keep deliverables on target. The WG on CP4-Africa itself has continued, in its three meetings this year, to monitor CP4-Africa output, discuss technical issues arising during the runs, to facilitate dissemination to the RCs and to plan and keep track of publications.

IMPALA has engaged with CCKE on a number of activities, including: organisation and delivery of the FCFA mid-term conference 4-8 September 2017, Cape Town, South Africa; contributions to the CCKE quarterly newsletters; utilisation of the FCFA Mobility and Innovation Funds (IMPALA now has 6 ECRs – see below); press release for the BAMS paper "Evaluating Climate Models with an African Lens"; the NERC Biannual Achievements Reports and the DFID annual review of FCFA; and with contributions to the FCFA website. Rachel James (WP3 – University of Oxford researcher on IMPALA and UMFULA) prepared and delivered a webinar entitled: "How can climate models be improved over Africa? Investigating global models with local knowledge" .

Ten IMPALA researchers participated in the FCFA mid-term conference with most making oral and/or poster presentations. The conference included two IMPALA-led side meetings/break out groups: a WP3 meeting on model evaluation led by Rachel James at which the concept of an African model evaluation hub was advanced with discussion of ideas on how to initiate it; and a parallel climate science session on "CP4-Africa and CMIP model data: analysis and use". IMPALA ECR Thompson Annor and core researcher Joseph Mutemi were assisted to attend the mid-term conference through access to the FCFA Mobility Fund. Richard Washington of University of Oxford has led IMPALA's engagement with the FCFA Mobility and Innovation funds. The 6 Early Career Researchers (ECRs) working with the 4 core Africa-based researchers (Table 1) are partly funded by the Innovation fund and partly by core IMPALA funding for WP3.

There have been three meetings of the MetUM Africa Process Evaluation Group (PEG), 27 April 2017 19 October 2017 and 26 April 2018. These meetings are increasingly sharing results from IMPALA research as well as Pillar 1 work in all 4 Regional Research Consortia. In particular, regular updates on CP4-Africa output are provided. All presentations are available on the collaboration twiki pages at: http://collab.metoffice.gov.uk/twiki/bin/view/Development/AfricaPEG.

An IMPALA science meeting was held at the University of Reading, 12-13 December 2017 and is the subject of this report. The meeting was attended by around 30 scientists engaged in the project and included representatives from all 4 Regional Consortia. The programme is attached at Appendix 1. IMPALA scientists, including senior scientists and ECRs from each of the four African institutions in IMPALA, presented their progress and plans on all work packages. Proceedings included a poster session in which posters prepared for the FCFA mid-term conference were displayed and discussed. One IMPALA ECR attended in person and the other Africa-based partners presented by video link. The Africa-based partner participating in person was Thompson Annor affiliated with KNUST Ghana and working with Benjamin Lamptey of ACMAD. An overview of Pillar 1 research progress in the 4 Regional Consortia was also presented as well as more detailed results from AMMA-2050 and

HyCRISTAL on use of the CP4-Africa simulations. Specific discussion sessions were held on cross-FCFA programme deliverables that will be led by IMPALA, specifically a CP4-Africa overview paper and a technical guidance document on CP4-Africa outputs (a summary of the discussions is in Appendix 2).

The Science Meeting also discussed the long-term storage of CP4-Africa data. We are in discussion with CEDA regarding long-term storage of a sub-set of CP4-Africa data on JASMIN. Work is on-going to agree the variables and time-periods but a proposal is under discussion which will encompass the most widely used data to make it easily available for those beyond FCFA. All the ~2PB of CP4-Africa data will also be stored indefinitely on the Met Office MASS storage system. Google Earth Engine is a candidate server for the data and a representative described its capabilities at the meeting. It is unclear as yet whether the remote processing/display facilities offered will serve project requirements.

Name	Home Institute	Core Researcher supervising	Research theme
Thompson Annor	KNUST	Ben Lamptey, ACMAD	Evaluation of the MetUM's West precipitation and temperature climatology over West Africa
Ridick Roland Takong	UCT	Babatunde Abiodun, UCT	Evaluation of the MetUM's simulation of season onset, cessation and the length of rainfall season in West Africa
Myra Naik			Assessment of the MetUM's simulation of drought patterns over West Africa
Giresse Kuete Gouandjo	Uni of Yaounde 1	Wilfried Pokam Mba, Uni of Yaounde 1	Deep understanding of regional mechanisms associated to rainfall variability over Central Africa. His work deals with better understanding of AEJ component dynamics, their links with regional mid tropospheric highs, divergence centres and diabatic heating.
Thierry Taguela Ndetatsin			Assessment of precipitation bias in the MetUM over Central Africa. His work is focuses on assessment of the link between atmospheric dynamic mechanisms over Central Africa and large scale circulation in the MetUM.
Anthony M Mwanthi	ICPAC/UoN	Joseph Mutemi, ICPAC/UoN	Evaluation of the MetUM over East Africa including for moist attributes and seasonal rainfall extremes

Table 1: IMPALA Early Career Researchers, Core Researchers supervising and research themes.

3. The MetUM development approach

The versions of the MetUM evaluated in most of the studies described in Section 4 are referred to as GA6/GC2, GA7/GC3 and proto-GA8/GC4. Here we give the origin of this nomenclature and also briefly describe the development cycle for the MetUM.

The MetUM undergoes continuous development by a large group of scientists working on improvement of model representation of dynamical and physical processes. The development cycle is defined by 1) the release of a new model version; 2) an extensive evaluation of its performance; 3) development, testing and incorporation of a suite of model changes and 4) release of the next version. The evaluation process (step 2) assists in identifying and prioritising the changes incorporated in step 3. Note that while some model changes can be developed, tested and implemented in a single cycle – most take several cycles to complete. A new atmospheric model version is usually released once each year. The Africa Process Evaluation Group (PEG) is a key activity led by the Met Office but including the UK modelling community which monitors the impact of model developments on performance for Africa and prioritises model developments for integration into the model.

The current "trunk" version of the MetUM is referred to as HadGEM3. Successive releases of HadGEM3 are identified in the global atmospheric (GA) model component as GA1,2,3 etc. More recently, a new series was started to explicitly define global coupled (GC) model releases. For example, GC2 refers to the standard coupled ocean-atmosphere configuration for which GA6 forms the atmospheric component. The baseline model version used in IMPALA is GA6/GC2 – the version when the project started. The next atmospheric release (GA8) has already been subject to extensive testing on preliminary versions and provided to the Africa-based IMPALA partners for evaluation studies. It is expected to be generally available for testing in June 2018, with GA9 available in spring 2019 (Table 2).

Version name	Release date	Model changes most relevant for African rainfall
GA6/GC2		Reference "baseline" version
GA7/GC3	January 2017	New UKCA-GLOMAP-MODE aerosol scheme; revised convection scheme; stochastic physics
GA8/GC4	Widely available June 2018 (already sent to Africa-based partners)	Prognostic entrainment for convection; increased detrained cloud, time damping of convective increments
GA9/GC5	Expected spring 2019	A number of convective changes are being worked on including; scale-awareness of convective triggering and closure; issues around timestep intermittency of convection; promotion of more persistent triggering of convection to reduce drizzle; and inclusion of a prognostic cold-pool forcing model.

Table 2: HadGEM3 model versions tested and to be tested in IMPALA

Evaluation experiments include use of global models of different horizontal resolution. In this report, some studies including evaluation at both N96 (135km) and N216 (60km) are presented – throwing light on the impact of resolution on model realism. May studies with the high resolution (4.5km) convection permitting pan-Africa regional model (CP4-Africa) are also included.

HadGEM3 contains major upgrades on HadGEM2, the previous “trunk” version, including a new dynamical core. HadGEM2, also underwent many development cycles including a branch of development leading to HadGEM2-ES a version which incorporates Earth System features (e.g. atmospheric chemistry). HadGEM2-ES remains a valuable tool for process understanding and is used in some IMPALA studies reported here.

Data analysis facility through JASMIN
University of Oxford have continued development of a facility on the Community Intercomparison Suite (CIS http://cistools.net) for the easy analysis of both IMPALA model and observation data. The tool is hosted on the NERC funded JASMIN cluster and allows users to collocate, aggregate and subset the project datasets using the power of JASMIN. Recent advances include improved collocation performance and support for reading many more satellite datasets. A number of papers are in preparation which have used the facility to perform model-observation inter-comparisons.

4. Progress

In this section progress reviewed at the December 2017 science meeting, hosted by the University of Reading, is presented. Each annual science meeting includes a large sample of work over all 4 Work Packages, this report covers mainly work presented at the science meeting. Full progress against all outputs are recorded in the FCFA logframe and annual report.

4.1 WP1: Influence of large-scale modes and teleconnections on African climate

WP1 is structured into the following sub-WPs each concerned with evaluating and improving the MetUM for different aspects of the large-scale influences on African climate.

- WP1.1 - dealing with (a) hemispheric-scale drivers of the global energy cycle and (b) large-scale modes of variability (e.g. ENSO) and teleconnections to Africa
- WP1.2 – Reducing uncertainty in the local (Africa) response to the large-scale forcing, focusing on (a) the role of resolution, ocean coupling and convective parameterisation in representing this response and (b) the role of sea-surface temperature (SST) biases in regions bordering Africa and (c) the role of local dynamics and thermodynamics.

WP1.1 Remote and large-scale drivers of African climate variability

WP1.1a: Sensitivity of model rainfall in the ITCZ over Africa to hemispheric albedo

Summary of previous findings
Results from the first year of this WP highlighted that corrections of the model imbalance in hemispheric albedo (southern hemisphere too dark) bring striking improvements in cross-equatorial energy and moisture transport, reduce the dry bias in the West African Monsoon and improve the northward “jump” associated with rainy onset in the Sahel. The albedo influence derives from its controls on incoming short-wave radiation and related energy budgets and transports.

Experiments with more realistic corrections to albedo were found to not reproduce these improvements and this led to further investigations exploring the sensitivity of cross-equatorial energy transport to the latitude at which the energy budget is perturbed. In general, the largest responses were seen for increased albedo in the tropical bands and in the experiments with the largest increases in albedo, with increases in the southern/northern hemisphere

associated with increased/decreased north-to-south atmospheric energy transport and more northerly/southerly positioning of the ITCZ (see last year's report Fig. 1a & 1b).

The results highlight the importance of the hemispheric energy budget controls on ITCZ (a major rain bearing system in the tropics) latitudinal positioning. They also highlight the persistence of model biases in the hemispheric energy balance that lead to a too southerly positioning of the ITCZ – one reason why the northern hemisphere monsoons are typically poorly represented in many models. The double-ITCZ problem[2], persistent in many models also appears tightly linked to errors in cross-equatorial energy transport.

This work has highlighted a number of other issues, including that model evaluation metrics based on RMSE that are frequently used to score performance by a number of centres, including the Met Office, miss out key information on compensating/additive biases across the hemispheres which can have major impacts on the representation of the tropical precipitation in particular. Additionally, the work has shown the importance of using coupled ocean-atmosphere models to study the energy balance, since it was found that the model's adjustments to meridional energy transport in the tropics – forced by perturbations in the energy budget – are achieved mostly via the ocean. This highlights a key weakness in many previous studies of inter-hemispheric energy transport that have used atmosphere-only or slab-ocean models where the dynamical response is confined to the atmosphere.

Work this period

Three peer reviewed papers have now been published describing the above results: Hawcroft et al. 2016, Haywood et al. 2016 and Stephens et al. 2016. A further paper Hawcroft et al. 2018 has been prepared and published this year.

Further experiments have been run in the last year exploring in greater depth sensitivity of cross-equatorial energy transport to latitudinally varying energy perturbations. Experiments have also been run as part of a wider model intercomparison study (Extratropical-Tropical Interaction MIP, ETIN-MIP: partners include University of Exeter, Ulsan National Institute of Science and Technology, NTU, GFDL) being co-led by an IMPALA researcher which will provide insights on the processes that govern dynamical responses to large-scale energy perturbations in both individual models and across an ensemble. Any spread in model response will provide information which will help discern the plausibility of future projections from models participating in the MIP, at both the global and regional scale.

Next steps

The ETIN-MIP being co-led from Exeter has 6 confirmed participants at the time of writing and initial experiments have been agreed (and already run on HadGEM2-ES). Analysis conducted as part of the MIP will be supplemented by evaluation of similar metrics in a perturbed parameter ensemble of the latest Hadley Centre model. Through these two routes, it will be possible to investigate inter and intra-model causes of differential behaviour which will assist in targeting the physical processes which are at the route of long-standing coupled model biases such as ITCZ positioning biases, the double-ITCZ problem and the (associated) representation of monsoon precipitation. Contributions to ETIN-MIP are likely to yield 3-4 papers prior to the end of the project. An initial BAMS paper is expected in 2018 from the MIP before further papers undertake in-depth analysis. Planned work evaluating a perturbed parameter ensemble of the latest Hadley Centre model should yield a further publication.

[2] Many climate models exhibit an unrealistic split or double structure to the tropical rainbands associated with the ITCZ

WP1.1b Errors in remote drivers and their pathways controlling African climate

Summary of previous work
Over the first two years work to characterise the MetUM's representation of the influences of ENSO, IOD, the Equatorial Atlantic, the Mascarene High, QBO and MJO on African climate has been advancing with emerging results documented in last year's report. Diagnostic techniques to measure model performance were developed and tested with key regions studied including West Africa (Sahel and Guinea coast) and East Africa (both the Short and Long Rains seasons). An example finding, further investigated in a CMIP ensemble analysis his year, were the spatial errors in the way model moisture transport into East Africa responds to Indian Ocean Dipole (IOD) and Mascarene High (MH) forcing.

This year consolidated results have been achieved in understanding the East Africa Short-Rains and Long-Rains – resulting in 2 published papers which are briefly summarised in the following two sub-sections

a) GHA Short Rains (SR) season

Previous work
The focus of this work, which feeds into IMPALA WP1.1 and WP1.2, is remote and large-scale drivers of variability in the East African Short Rains (EASR). Previous findings confirmed that wet EASR seasons (October-December) are associated with a positive Indian Ocean Dipole (IOD) and El Niño conditions in the central and eastern Pacific. Generally, the MetUM is able to capture the large-scale SST pattern leading to enhanced rainfall over East Africa. In the previous report initial results from GC2 and GA6 at N216 and N96 horizontal resolution were shown.

This period
This year analysis has been extended to the new GC3 and GA7 releases of the MetUM (Table 2), as well as to the full ensemble of coupled and atmosphere-only models that make up the CMIP5 archive. This work, summarised below, has now been published online in the Journal of Climate (Hirons and Turner: "The impact of Indian Ocean mean-state biases in climate models on the representation of the East African short rains").

Analysis of 30 atmosphere-only (AMIP) and 48 coupled (CMIP) models from CMIP5 has shown that all models overestimate the strength of the EASR. This overestimation is worse in models that are not able to accurately capture the mean state in the Indian Ocean. Specifically, about half of the models exhibit low-level easterlies in the equatorial Indian Ocean rather than the observed westerlies and it is the models with easterly mean state that exhibit the largest precipitation biases during the EASR (hereafter we refer to "easterly/westerly" models for those with an easterly/westerly mean state). Although the wet EASR bias is slightly improved in the AMIP models, it is still present and almost half of the 30 AMIP models still exhibit mean low-level easterlies in the equatorial Indian Ocean during the season.

During a positive IOD all models show an increase of moisture advected towards East Africa. However, the observed latitudinal structure of that moisture advection - with an equatorial "dip" (black line; Fig. 1) - is best captured by the westerly models (green lines; Fig. 1) with their closer-to-observed mean state in the Indian Ocean. Those models with erroneous easterly winds in the equatorial Indian Ocean (red lines; Fig. 1) are unable to capture the observed equatorial dip in moisture advection and instead show a single strong peak of moisture just south of the equator. Furthermore, the associated anomalous easterly surface wind stress causes upwelling in the eastern Indian Ocean, enhances the zonal SST gradient between east and west and strengthens the positive IOD pattern, further amplifying the easterly wind stress. This positive Bjerknes coupled feedback is stronger in easterly mean-state models, which

results in a larger EASR wet bias in those models. These findings are summarized schematically in Fig. 2.

A similar analysis has been carried out with the atmosphere-only MetUM GA6 and GA7 simulations compared to their coupled counterparts GC2 and GC3. Atmosphere-only versions of the MetUM are able to capture the observed low-level westerlies (as in Fig. 2 (a)) in the equatorial Indian Ocean, whereas the coupled versions exhibit erroneous easterlies (as in Fig. 2 (b)). This leads to the coupled versions being unable to capture the observed latitudinal structure of moisture advection during a positive IOD and a larger EASR wet bias (as in Fig. 2 (d)).

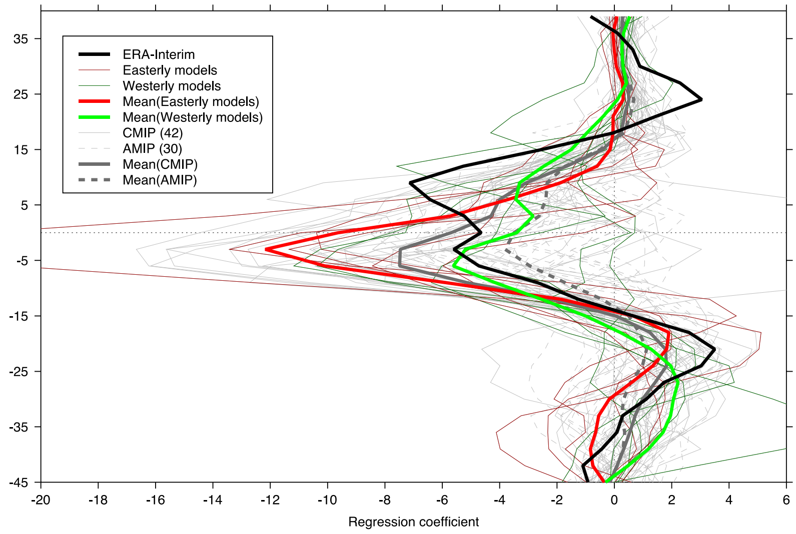


Figure 1: Vertically integrated moisture flux (uq) going along each latitude at 56°E regressed onto the IOD index. The thick black line represents ERA-Interim. Individual CMIP and AMIP models are represented by thin dashed and solid grey lines, with the AMIP and CMIP means represented by thick dashed and solid grey lines, respectively. The 6 easterly and 6 westerly models are represented by the thin red and green lines, with the easterly and westerly means represented by thick red and green lines, respectively.

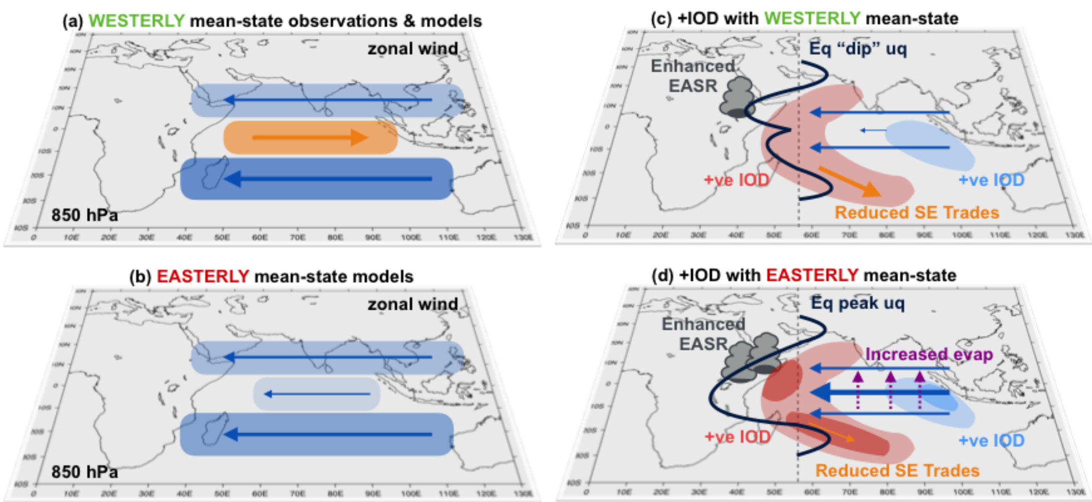


Figure 2: (a,b) Schematic representation of models with a westerly and easterly mean-state, respectively. (c,d) Schematic representation of the response of a westerly and easterly model to a positive IOD.

Next steps
This work will be extended by examining case studies of CP4-Africa responses to large-scale teleconnected drivers (such as the IOD and ENSO) in both present-day and future climate simulations. Specifically, in the case of the EASR, the moisture fluxes at the CP4-Africa domain boundary will be analysed.

b) MAM Long Rains (LR) season

Previous work
Variability in the East Africa LR (EALR) season is not significantly linked to variability in tropical Pacific and Indian Ocean SST, as in the EASR case (see above). Studies of drivers of variability in the EALR over the preceding two years have confirmed that the MJO and QBO have moderately strong links to season variability, strongly exceeding the (near absent) constraints by tropical SST. In addition, diabatic heating anomalies over the Maritime Continent (MC) and SST variability in the northern Indian Ocean also appear potentially important. A supplementary outcome, of high interest to other studies, is that we have established the fidelity of modern reanalyses in reproducing the instrumental rainfall record between 1980-2016. This gives us the confidence that the relevant dynamical processes in the reanalyses (i.e. models constrained by observations) are realistic. This is an important conclusion given the challenges faced by models in representing rainfall over the region.

This period
This year we have concluded our study on remote drivers of interannual variability of the EALR. The results have now been published in QJRMS (Vellinga and Milton 2018). The headline results are summarised below.

- We analysed three important drivers: regional Indian Ocean SST, seasonal amplitude of the Madden-Julian oscillation (MJO) (shown in last year's report to be a key driver) and phase of the quasi-biennial oscillation (QBO). Common to all three drivers is their ability to modify the large-scale subsidence over the East African region during boreal spring. SST in the western Indian Ocean achieves this via anomalous boundary layer heating of the lower troposphere. The MJO modifies subsidence over the region through anomalous ascent and descent. Rainfall over East Africa responds to this MJO forcing in a uni-directional way: periods of opposite-signed forcing from sub-seasonal activity of the MJO do not cancel out over the seasonal timescale. This means there is a residual, seasonal mean rainfall impact that varies from year-to-year and that depends on the overall MJO activity in a given year. The QBO's influence is weak in reanalyses and understanding it is complicated by the limited number of cycles over the reanalysis period.
- Each driver individually has a modest effect on the Long Rains. However, added together they explain ⅓- ⅔ of the total variance of yearly variability across the region as a whole, depending on dataset (shown for MERRA2 reanalyses in Fig. 3). The mechanisms we discuss suggest priorities for model development to improve model variability over East Africa: mean subsidence over the western Indian Ocean associated with the Hadley and Walker circulations, correct phase locking of ENSO and IOD to exclude undue teleconnections to the EALR by these SST modes; improved representation of the MJO.

Next steps
The metrics developed lend themselves for easy evaluation of the remote drivers in models and other datasets. Future work will evaluate these drivers in UM models with the aim to link deficiencies in the representation of remote drivers to errors in the models' mean state.

As a preview of analyses starting for the final year of IMPALA, evaluation of the MJO relationship with EALR variability in proto- GC4 is compared against that of the previous model

version (GC3) in Fig. 4. The MJO is a convectively coupled oscillation and proto-GC4, which contains improvements to convection scheme (prognostic entrainment – see Section 4.2) exhibits a much better representation of MJO forcing of March-April rainfall over East Africa (ref Fig 4b and 4c) relative to GC3 which exhibited very little rainfall response to MJO (Fig. 4a).

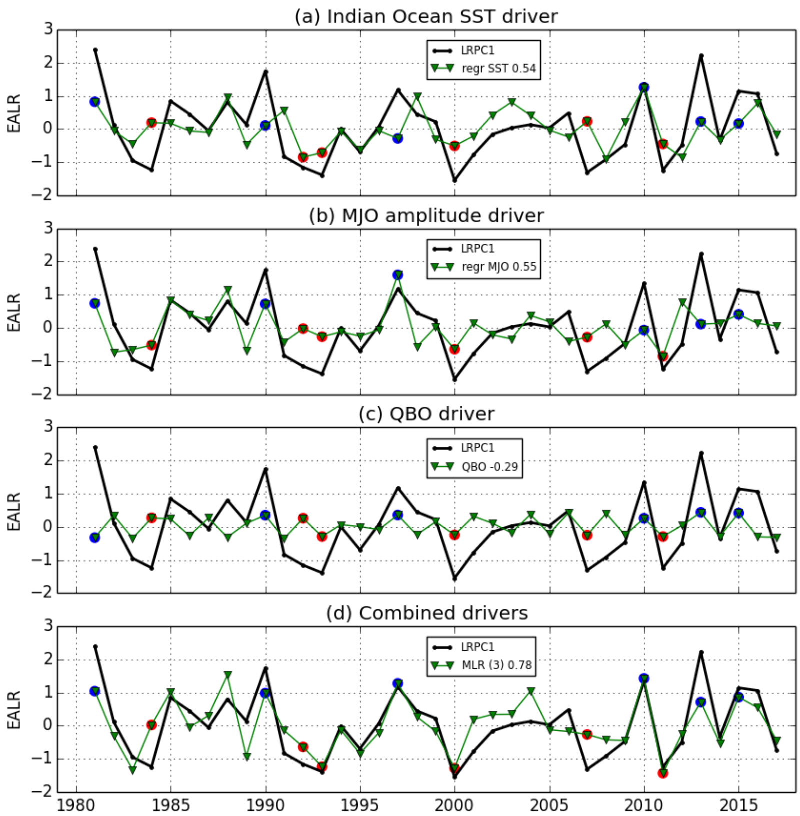


Figure 3: E African Long Rains variability and its relation to three drivers (1981-2017). In (a-c) each driver timeseries is regressed individually onto EALR time series (black curve). The 'predicted' EALR timeseries obtained from this regression is shown in green, its correlation with the actual EALR is shown in the panel legends. (a) March-April mean Indian Ocean SST averaged over 5-20°N, 55-80°E (b) Feb-Mar mean (RMM1, RMM2) MJO amplitude (c) QBO during SON of the preceding year. (d) Multiple linear regression of three drivers from (a-c) onto LRPC1. Blue (red) circles denote the six wettest (driest) EALR years in MERRA2.

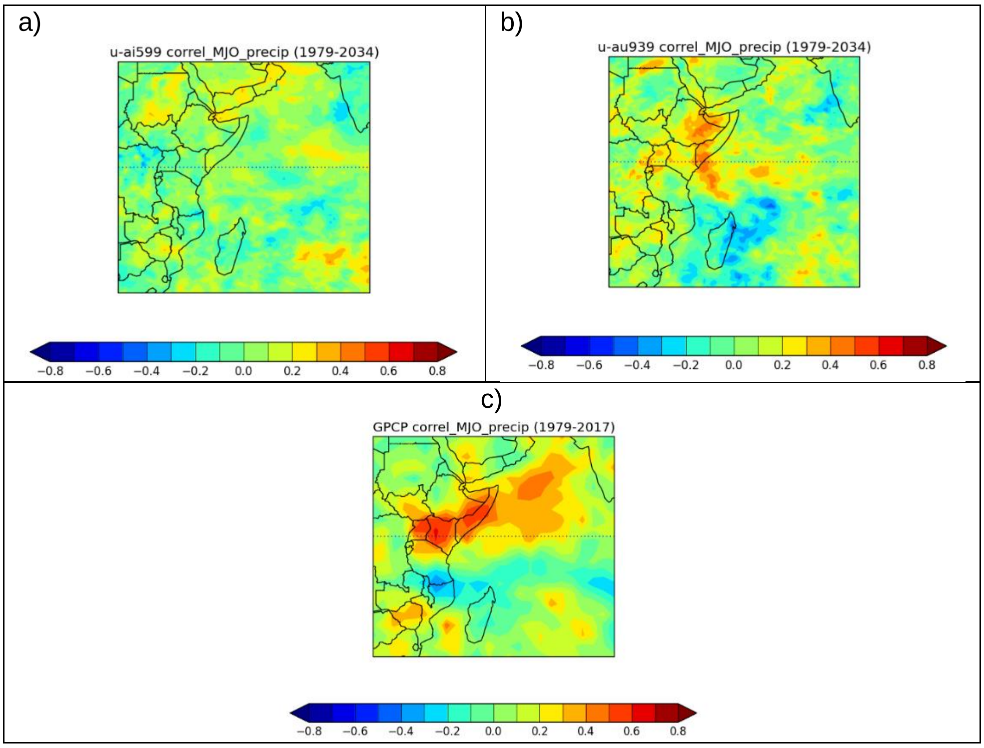


Figure 4: Correlation of the average February-March MJO amplitude with March-April rainfall. a) in GC3; b) GC4 (both 1979-2034) and c) observed MJO (from Australian Bureau of Meteorology and observed rainfall (GPCP).

c) Remote and large-scale drivers of variability in the West African Monsoon

A further focus has been on assessing the MetUM's representation of the West African Monsoon (WAM). In observations, enhanced Guinea Coast rainfall during July – September (JAS) is associated with warm SSTs in the equatorial Atlantic. Previous work has analysed this teleconnection in the GA6 and GC2 simulations, this year the work has been extended to analysis of the latest GA7 and GC3 MetUM versions. This teleconnection pattern is reasonably well captured in all MetUM simulations, with the exception of GC2-N96 (not shown).

More generally for West Africa, including the Sahel region, the MetUM simulations are not able to accurately capture the vertical structure of the WAM. Most coupled versions exhibit two distinct peaks in the main ascent region rather than one broad inland peak (Fig. 4). Additionally, the mean precipitation seems to be uncoupled from the main ascent region and the African Easterly Jet (AEJ), centred near 600mb, is co-located with the region of ascent in the simulations, rather than slightly further north of the ascent maximum as in observations (Fig. 4).

Further analysis is required to understand these findings, however, there are important relevant errors in the mean state. For example, in the MetUM the AEJ is too strong and too broad and there is insufficient interannual variability in its southern flank (not shown), although there are indications this is improved in GA7/GC3 compared with GA6/GC2. Furthermore, the main rain belt does not progress far enough north across the continent during the monsoon season.

Next steps

We intend to extend this West African summer monsoon analysis to CMIP5 with the aim of linking monsoon and AEJ diagnostics to large-scale behaviour.

d) Diagnosing remotely forced systematic errors over Africa

Understanding climate model errors through similarity with errors in short-range prediction:
The large-scale 850hPa error structure is characterised by excessive convergence into tropical south America and excessive divergence over the maritime continent together with a smaller convergence error over Africa and smaller divergence error over the tropical Atlantic. The tropical error structure in the 5-day forecasts is very similar to that in the AMIP simulation (Fig. 5) which allows us to understand the error in the climate simulation by studying the rapid development of the errors in the NWP model. In the NWP model spurious heat lows of similar size develop over both Africa and south America at short forecast times which result in excessive convergence; this is possibly due to a lack of cloud over land. The convergence error over south America continues to grow throughout the forecast, and ultimately dominates on climate timescales, whilst the convergence error over Africa initially grows but then reduces with forecast time. It is speculated that this could be caused by either the asymmetrical dynamical response which could allow excessive ascent over south America to suppress the error growth over Africa (see following section on “nudging”). Alternatively, it could be due to the warmer sea surface temperatures (SSTs) in the western tropical Atlantic, which when combined with the convergence error would bring in warm moist air and hence provide a positive feedback on the convergence error, and cooler SSTs in the eastern tropical Atlantic, which will feedback negatively on the convergence error. Similar error structures are also seen in both AMIP and NWP in June, July August (JJA). Furthermore, the African Easterly Jet (AEJ) and errors in the AEJ can be shown in the NWP model to be predominantly geostrophic. The broadening and equatorward shift in the AEJ, which is seen in both AMIP and NWP simulations, can be explained in terms of errors in the geopotential height and hence in temperature and surface pressure. In summary, climate circulation errors can often be seen on NWP timescales and hence the NWP model is a useful tool in understanding these errors in terms of their development and structure.

The “nudging” diagnostic technique:
The nudging simulations to investigate the remote vs local forcing of model systematic errors over Africa have been further developed and a large number of potential remote source regions for forcing of African model errors have been investigated. The adjacent South Asian summer monsoon region remains one of the key driving regions for errors in the mean state of upper-tropospheric winds over Africa (tropical easterly jet at 200hPa). This points to a need to improve the wider Asian Summer Monsoon circulation biases, and developments implemented to the UM convection scheme at proto-GA8/GC4 (convective memory) and planned for GA9/GC5 (scale aware convection scheme – COMORPH) are targeted at addressing such biases. However, this region has less influence on wind biases in the mid-troposphere (African Easterly Jet) and boundary layer (west African monsoon inflow), which appear to be more influenced by locally generated errors over Africa itself. Surprisingly, remote errors over adjacent regions to the west, such as South America and the East Pacific have only a small influence on the African circulation biases. In the context of the wider global circulation the model errors over west and Central Africa themselves have a huge influence on biases in the Southern Hemisphere/Southern Ocean circulation in JJA, which in turn influences the veracity of climate model simulations over South Africa.

Next steps
Work is underway to also assess the impacts of correcting key model biases through nudging on inter-annual variability and the teleconnections to Africa. We are also planning to perform nudging experiments at the NWP timescale to study how the remotely forced errors propagate through to Africa. This should give greater understanding of the dynamics of the error growth and of the sources of the initial errors.

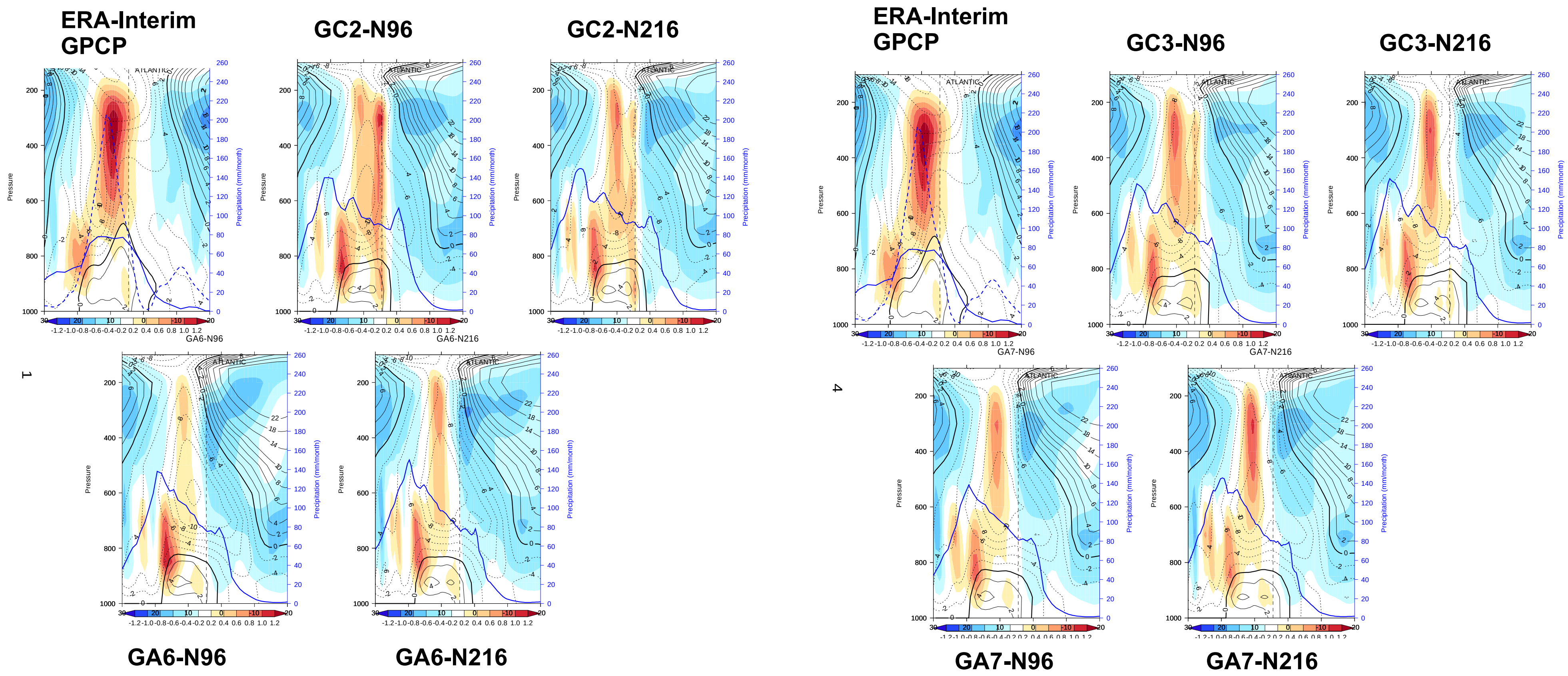


Figure 4: Vertical structure of August mean vertical velocity (colours) and zonal wind (contours) averaged between 10W and 10E. Averaged precipitation (blue line). Top row: ERA-Interim and coupled simulations (GC2 left; GC3 right). Bottom row: AMIP simulations (GA6 left; GA7 right). North is to the left of each plot. The ERA-Interim plots also show the averaged GPCP rainfall (dashed blue line)

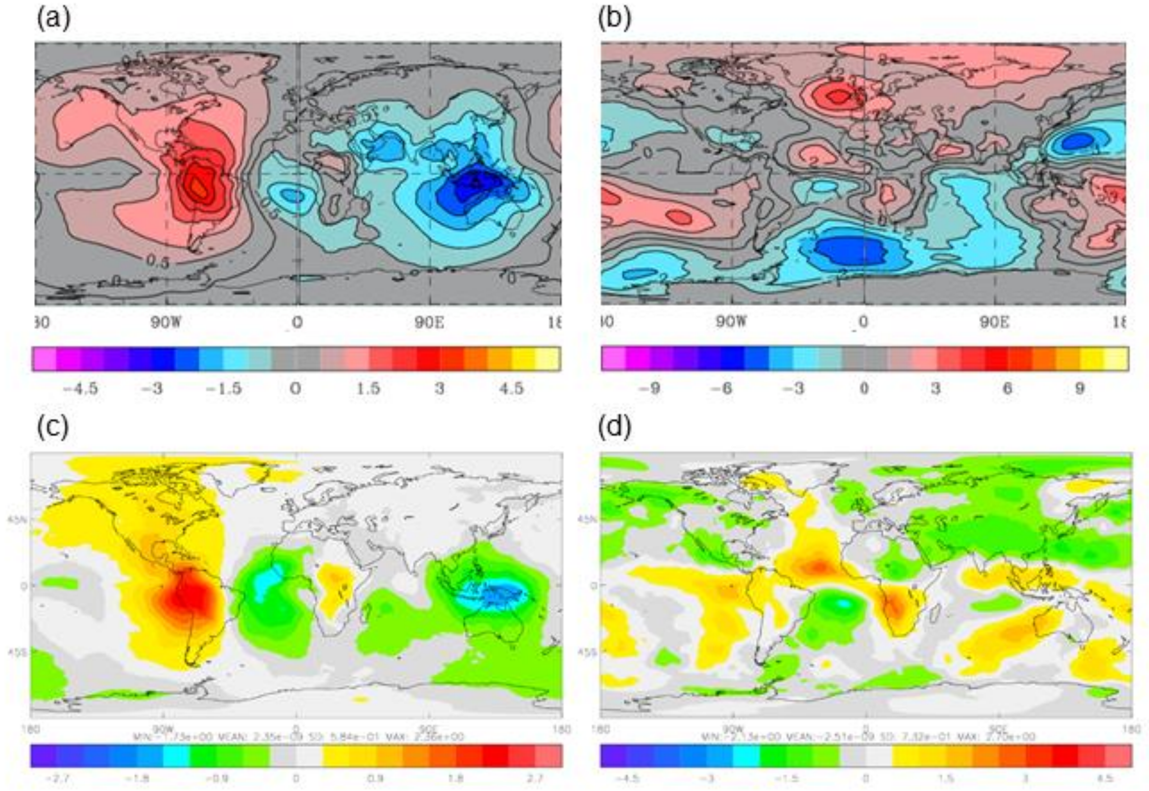


Figure 5: The September, October and November (SON) mean error at 850hPa in (a) velocity potential and (b) streamfunction for a 20-year AMIP simulation and for (c) velocity potential and (d) streamfunction for the Met Office's operational NWP global model in 2016. The error in the AMIP simulation is calculated with respect to ERA-I reanalysis and the error in the NWP model is calculated as the difference between the 5-day forecast and the model's own analysis.

4.2 WP2: Improved representation of local processes

W2.1 Convection parameterisation development

a) Improving the representation of sub-grid moist convection in the MetUM

A major weakness in climate models - representation of tropical convection - continues to be addressed. Work reported last year on significant improvements to the convection scheme on: a) "timestep intermittency"; b) a tendency to trigger convective rainfall too homogeneously and c) "scale awareness" issues, is beginning to pull through to the operational MetUM. In particular, the prognostic convective entrainment improvement has been implemented in MetUM version proto-GA8/GC4. This modification generates a more realistic, slower build-up of convective storms and improves the modelled peak in the diurnal cycle – which occurs too early in the day in the tropics – and also improves representation of African Easterly Waves.

Scale-awareness in the convection scheme

A focus this year has been on improving the scale-awareness of the MetUM convection scheme. This is important because the MetUM has configurations at a wide range of resolutions – from 100s of kilometres to e.g. 4.5km in the CP4-Africa model. The convection scheme should be capable of responding correctly at different resolutions such that the resolved and unresolved processes are realistically partitioned at all resolutions. Research has suggested that the closure of such a scale-aware scheme is more appropriately based

on mass flux at the cloud base rather than convective available potential energy (CAPE) – as at present. Coding of a new scheme is in progress and testing for inclusion in MetUM version GA9 (December 2018) is underway.

b) The CP4-Africa simulations: present-day and idealised future

Present-day simulation: The CP4-Africa control simulation completed 10 years (1997-2006) in early November 2017. Ten-year seasonal means have been created from the simulation and compared with the same 10 years from the regional, non-convection permitting 25km "control" model (nCP25-Africa) and the global model - both running with convective parametrization. All three models' seasonal means have been compared with a selection of climatologies to assess their performance. Overall the findings are similar to an earlier comparison using five-year means that has been published this period in Stratton el al. 2018, and to results reported last year with 3 years and 2 months of simulations. In general, there are reduced biases in CP4-Africa simulations. Specific improvements, relative to nCP25-Africa and global driving model include the following. The JJA mean precipitation of the CP4-Africa model is better over Western Africa substantially reducing the long-standing dry bias seen in the other models (Fig. 6). In DJF (not shown) the over prediction of precipitation over southern Africa is reduced. Instances with increased biases in CP4-Africa include too much precipitation in JJA and DJF along the ITCZ over the ocean. Over the stratocumulus region to the west of Africa, particularly where cloud-aerosol interactions are important, both regional models perform rather worse than the global model, at least partly due to the simplified representation of aerosols in these models.

Encouragingly, the initial results presented here suggest that the variability and spatio-temporal characteristics of the rainfall all appear to be better represented in the CP4-Africa model. There is evidence of westward propagating convective systems and a better intensity/frequency distribution of 3-hourly precipitation events (Fig. 7). The diurnal cycle of convective precipitation over land is better handled in CP4-Africa and the most extreme intense but short-lived rainfall events are also better captured.

Other systematic differences between the CP4-Africa and nCP25-Africa simulations have also been investigated and include: 1) the CP4-Africa 1.5m temperatures are colder almost everywhere over land - differences being largest in the regions with convection; 2) convective regions in the CP4-Africa simulations have far more cloud condensate than the nCP25-Africa model; 3) above about 600hPa the CP4 model is warmer, below this it is cooler (Fig. 8) – in most places these differences are beneficial.

These differences improve agreement with ERA-Interim in most seasons and regions examined and are mainly due to the use of a convective permitting model. Some could be due to the difference in the cloud scheme, the additional vertical resolution in the lowest 5km and use of the blended boundary layer scheme at higher resolution. Comparison of the global and nCP25-Africa seasonal means show little difference apart from in the top of atmosphere outgoing short-wave radiation over the ocean to the West of Africa. This difference is thought to be related to the difference in the aerosols in the global and regional models and their impact on the low-level stratocumulus cloud in the region.

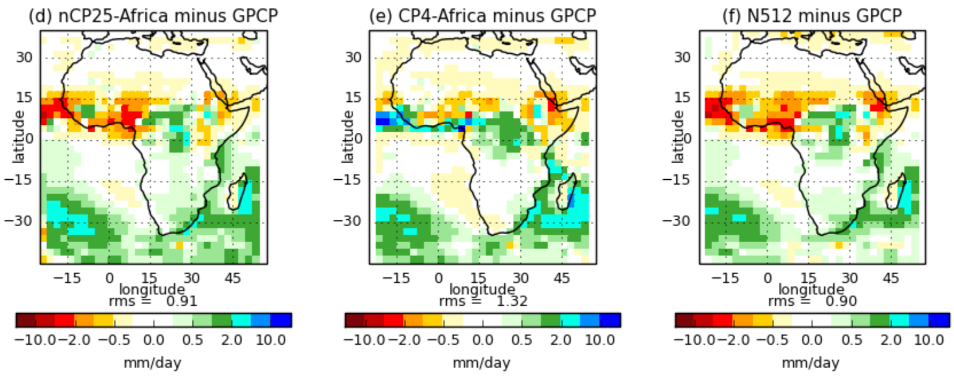


Figure 6: Bias in JJA seasonal mean precipitation 1997-2006 relative to GPCP, left, nCP25-Africa; middle, CP4-Africa; right, global model at N512 resolution.

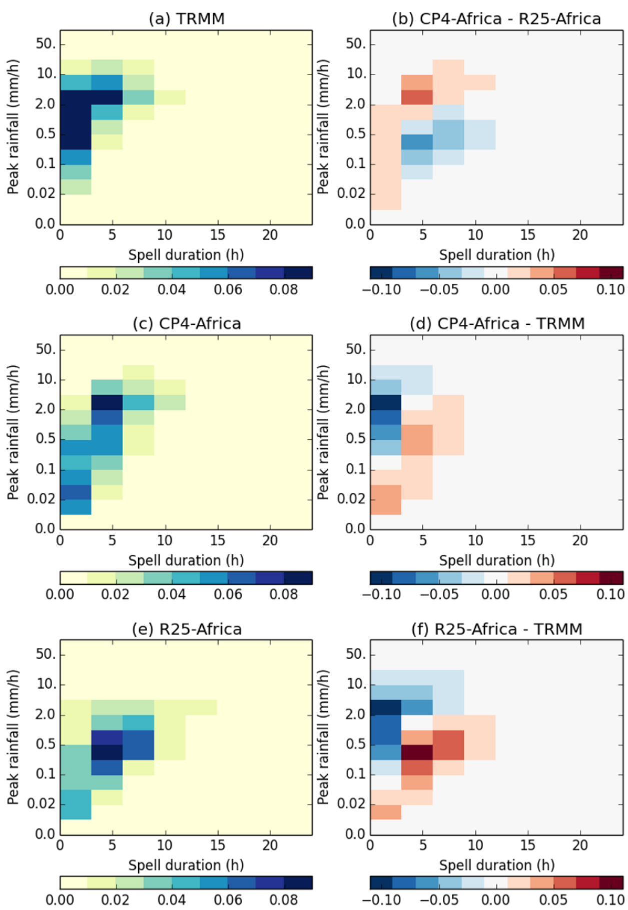


Figure 7: The joint probability distribution of wet spell duration versus peak rainfall intensity for the West African monsoon region (15°W-10°E, 8°-17°N) for JJA 1998-2001 (from Stratton et al. 2018). The plots show the distribution for TRMM, CP4-Africa and nCP25-Africa plus differences.

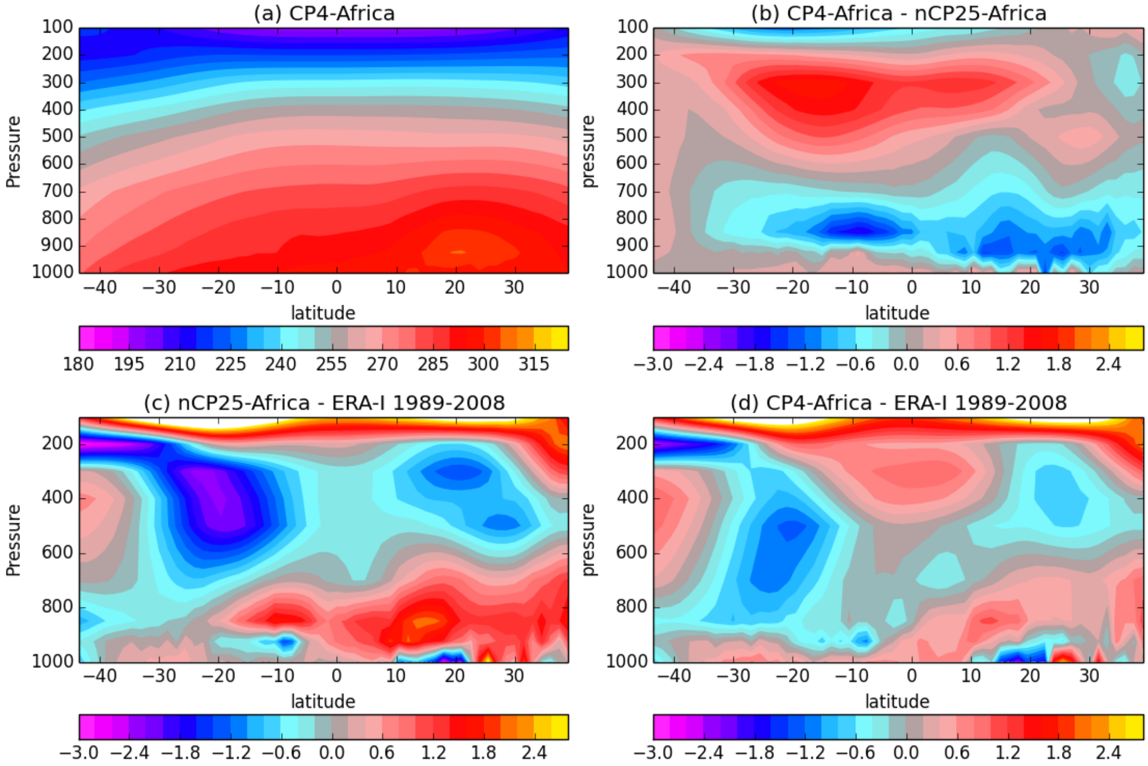


Figure 8: Comparison of biases relative to ERA interim in CP4-Africa and nCP25-Africa 10-year mean zonal mean JJA temperature, a) CP4-Africa; b) CP4-Africa – nCP25-Africa; c) nCP25-Africa – ERA-I; CP4-Africa – ERA-I. Zonal means are calculated over the full CP4-Africa domain.

Idealised future simulation: The CP4-Africa idealised future simulation, representative of 2100, has completed 7 years to date. Analysis of these runs, indicates that future increases in extreme 3-hourly (and to a lesser extent daily) precipitation are greater in CP4-Africa compared to the nCP25-Africa regional model. Also, at the same time, we see a greater tendency for a lengthening of dry spells during the wet season in CP4-Africa. These results give a first insight into how the improved representation of convection in CP4-Africa impacts on projections of future climate change across Africa.

c) Further analysis of CP4-Africa simulations, including from Regional Consortia

In addition to the broad-based studies giving a general analysis of the pan-Africa performance of CP4-Africa, a number of studies focussed on specific aspects and/or regions are emerging and are summarised below.

i. Heatwaves

Heatwaves have a significant impact on human mortality and crop production in Africa. There have been several recent studies of African heatwaves, using non-convection-permitting regional climate model simulations (CORDEX, 25-50km horizontal resolution; Dosio, 2016; Russo et al. 2016). Both predict increases in heatwave intensity and frequency in future climate, however, projections could be different in higher resolution models and those with a better representation of rainfall and convection. The aims of this study are to:

- Determine how the representation of present-day heatwaves differs between CP4-Africa and more traditional climate models

- Determine whether projections of heatwaves under future climate are different in CP4-Africa
- Understand the reasons for the differences, candidates being differences in convection, rainfall, diurnal cycle, cloud, model resolution

The simulation data used is shown in Table 3 with abbreviations used to for CP4-Africa and nCP25-Africa to distinguish between present-day (PD) and future idealised climate (FC) simulations.

Data set	**Abbreviation**	**Years used**
Present day N512	25kmPD	1997-2006 (10 years)
Future climate N512	25kmFC	1997-2006 (10 years)
Present day CP4-Africa	4kmPD	1997-2002, 2004-2005 (8 years)
Future climate CP4-Africa	4kmFC	Not included here

Table 3: Present-day and future simulations used in the heatwaves study

A pan-Africa heatwave analysis has been undertaken, using land points only. The CP4-Africa data is subsampled to every 6th gridbox to resemble the 25km grid of the nCP25-Africa model. A sensible subset of the nCP25-Africa data is used for direct comparison with the CP4-Africa years.

Method

Heatwaves in the present-day simulations are identified using the method outlined by Russo et al. (2015): the HeatWave Magnitude Index – daily (HWMId), see Fig. 9. The advantages of this method are (1) that percentile thresholds are used allowing for differences in absolute values of temperature in the model simulations, (2) it is a gridbox-by-gridbox calculation allowing for the different seasons and climatic zones in Africa and (3) it combines heatwave intensity and duration into a single number.

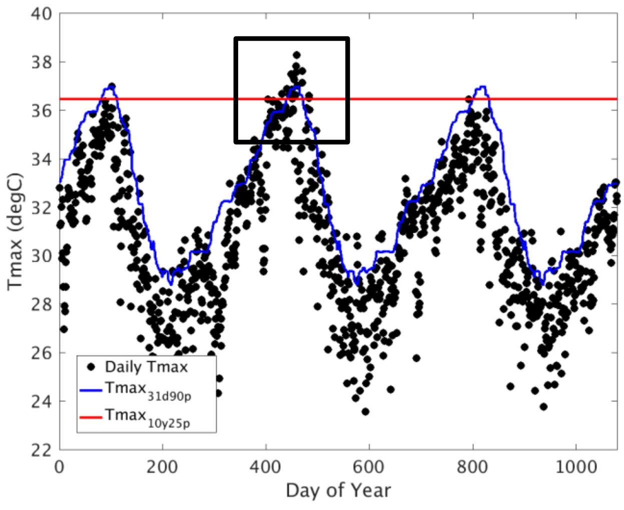


Figure 9: Example data from CP4-Africa (4kmPD), showing the daily T_{max} values for a period of two years over a single gridbox (black dots). Heatwaves are identified when the daily T_{max} is greater than the 90th percentile of daily T_{max}, computed along a running 31-day window (blue line) and greater than the 90th percentile of annual T_{max} (red line). The HWMId is computed for each identified heatwave day using Equation 2 in Russo et al. (2015). The calculation for the future climate data uses the present-day baseline (i.e. the same red and blue lines).

Near-surface temperature bias

25kmPD is warmer than 4kmPD in all seasons and all regions (Fig.10a – also Fig. 8b). This is mostly limited to the boundary layer (Fig. 10b), suggesting the difference is driven by the surface. The 25kmPD has more downward short-wave radiation SW_{dn} at the surface than 4kmPD, which results in a higher surface sensible heat flux in 25kmPD, which warms the near-surface (Fig. 10c). The difference in SW_{dn} is likely due to differences in cloud between the two models. There are phase differences in the diurnal cycle of cloud (Fig. 10d) but the main cause of the SW_{dn} differences is more likely the total amount of cloud and its reflectivity – cloud top is higher and/or colder in 4kmPD (at most times) than 25kmPD (Fig. 10d).

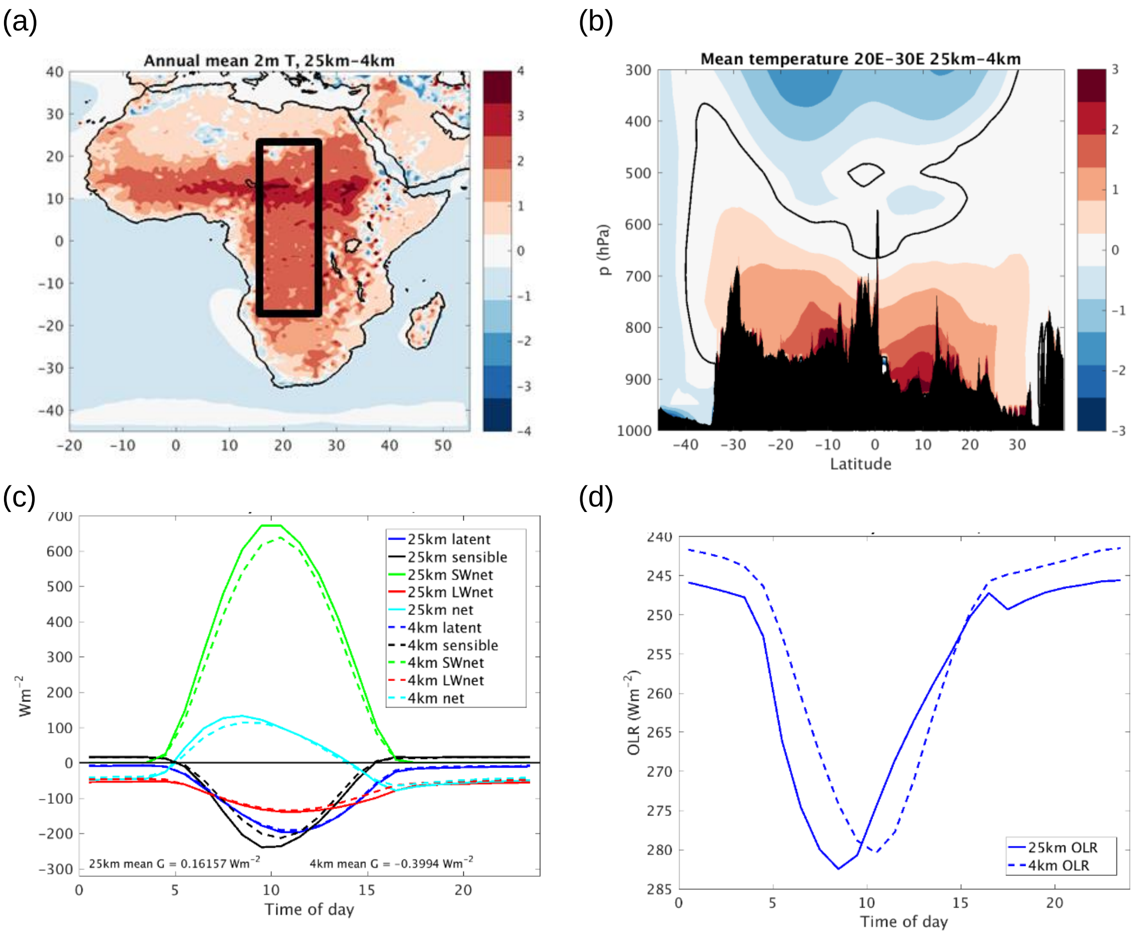


Figure 10: (a) difference between 25kmPD and 4kmPD in annual mean near-surface temperature, (b) difference between 25kmPD and 4kmPD in annual mean temperature, averaged along the longitudes marked by the box in (a), (c) the mean diurnal cycle of the components of the surface energy budget and (d) the mean diurnal cycle of outgoing longwave radiation. (c) and (d) are averaged over the box in (a).

More heatwaves were diagnosed in 4kmPD than 25kmPD (Fig. 11). There is high interannual variability, although the variability is similar in the two simulations, suggesting that the model boundary conditions and/or the SSTs have a significant control. The magnitude of each heatwave is, on average, higher in 4kmPD than 25kmPD (Fig.12a-c). In 25kmFC, the magnitude of the diagnosed heatwaves are an order of magnitude higher, especially over the Sahara region (Fig.12d-e).

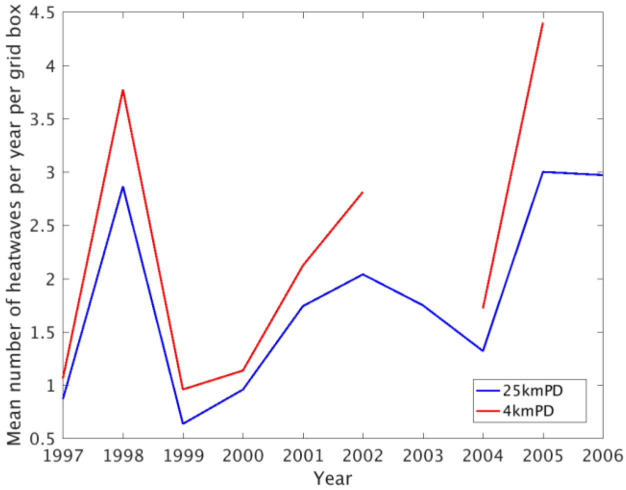


Figure 11: Mean number of heatwaves per gridbox per year.

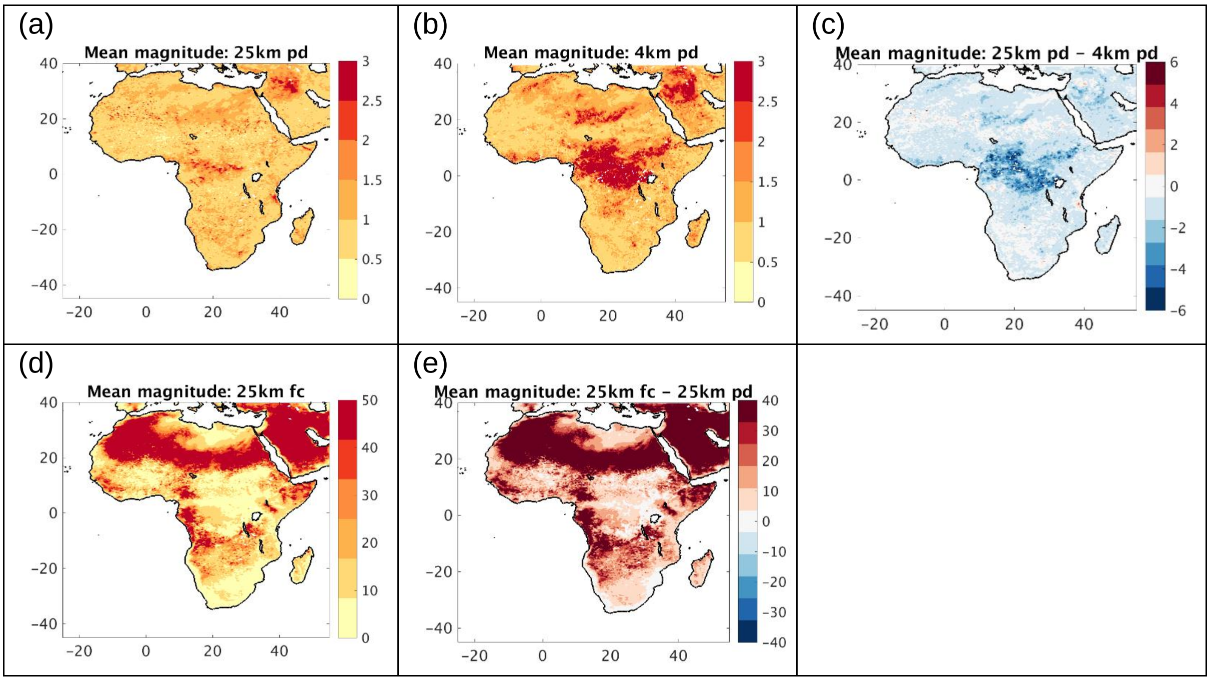


Figure 12: Mean magnitude of heatwaves: a) nCP25-Africa present day (25kmPD); b) CP4-Africa present day (4kmPD); c) differences 25kmPD-4kmPD; d) nCP25-Africa future simulations (25kmFC); e) difference 25kmFC- 25kmPD.

The 25kmPD and 4kmPD simulations have the most heatwaves in the months preceding the main rainy season, which is the anticipated result as these seasons tends to be the hottest (Fig. 13). In 25kmFC however, the month with the most heatwaves is much noisier, and there are abrupt changes in the Sahel, for example, which require further investigation.

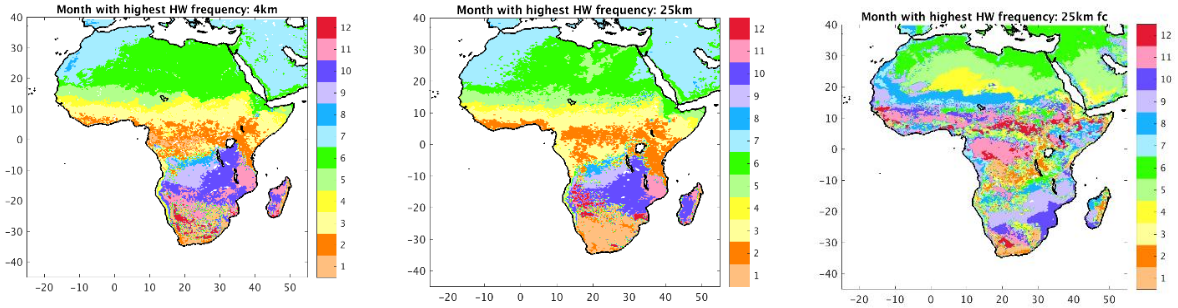


Figure 13: Month of the year with the most heatwaves, a) CP4-Africa present-day; b) nCP25-Africa present-day; c) nCP25-Africa future.

Conclusions and next steps

Near-surface temperatures in 25kmPD are warmer than 4kmPD due to cloud differences. The 4kmPD simulations have more frequent and more intense heatwaves than 25kmPD. Heatwaves are far longer, more numerous and more intense in 25kmFC compared to 25kmPD.

The next steps are to:

- Analyse present day cloud diagnostics
- Understand reasons for 25kmPD versus 4kmPD heatwave differences – likely candidates are differences in convection/rainfall/cloud/resolution.
- Compute heatwave diagnostics for 4kmFC
- Understand effect of sub-sampling 4km versus interpolating it onto 25km grid for extremes
- Diagnose the spatial extent/coherency of heatwaves

ii. The Annual Cycle of Convection and Rainfall in the Hadley cell over Central Africa

Work this year started on the evaluation of the performance of convection schemes over the African continent under the IMPALA deliverable WP2.1c. Data from the pan-Africa convection permitting CP4-Africa simulation and the parameterised convection 25km resolution control simulation (nCP25-Africa) were used. Results are based on 10 years' data for the current climate simulations. Provisional results for the future climate simulations are based on 10 years' data for nCP25-Africa and 3 years' data for CP4-Africa.

The annual cycle in monthly mean Hadley circulation over continental Africa is shown in Fig. 14 for nCP25-Africa and CP4-Africa and compared with ERA-Interim re-analysis for the same domain and time period. nCP25-Africa, CP4-Africa and ERA-Interim re-analysis have the same dynamical features in the mean Hadley cell circulation and the associated tropical rain-belt. The precipitation and region of strong convection migrate north and south through the annual cycle following the latitudes of strong insolation with a lag of approximately one month. The intense precipitation associated with the tropical rain-belt is co-located with strong ascent at 500hPa and frequently with subsidence and divergence at lower levels in the troposphere. The region of strong convection and precipitation is bordered to the north and south by the African easterly jets. To the north of the main rain-belt, there is a persistent region of low-level convergence and shallow convection that is associated with relatively light precipitation. To the south of the rain-belt, the region of low-level convergence and shallow convection is seasonal and prevalent from May to September. Differences in the representation of convection in CP4-Africa and nCP25-Africa result in key differences in Hadley cell circulations. CP4-Africa has more intense large-scale subsidence in the subsiding

regions of the Hadley cell, more intense mean ascent in the upper troposphere but less intense mean ascent in the lower and mid-troposphere.

To evaluate the differences in convection between nCP25-Africa and CP4-Africa, the differences in precipitation and vertical velocity at 500hPa (w500) are shown in Figs 15a&b. Precipitation within the central core of the rain-belt was intensified in CP4-Africa compared to nCP25-Africa. There was also a southward shift in precipitation in November to April, increased precipitation associated with the West African monsoon, and a widespread decrease in precipitation to the north and south of the tropical rain-belt. Changes in the seasonal and zonal mean precipitation were strongly correlated with changes in the intensity of w500.

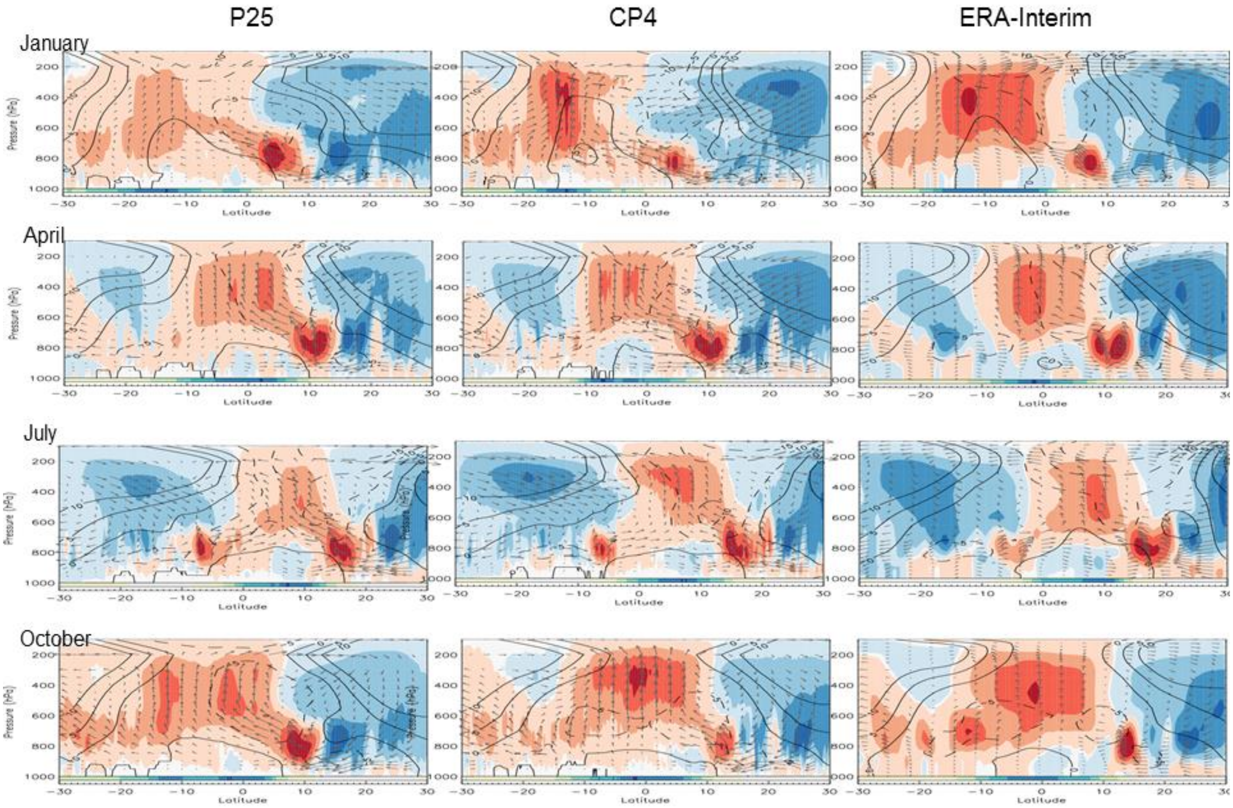


Figure 14: A height Vs latitude cross-section of the monthly mean Hadley cell circulation over continental Africa (15ºE to 30ºE and 30ºS to 30ºN). The cross-sections are based on monthly mean data from 1997-2006 (current climate). Zonal winds are represented by the contour lines with solid lines denoting westerly winds and dashed lines easterly winds. Meridional winds are represented by arrows. Vertical velocity is represented by shading with red colours denoting ascent and blue colours descent. The precipitation rate is represented by the horizontal colour bar at the bottom of each panel.

Explicit convection produced more extreme ascent and descent at 500hPa than parameterised convection and mean vertical velocity was more strongly linked to rainfall. For example, about the equator in February, a region and season of both high precipitation and large change in precipitation between CP4-Africa and nCP25-Africa, mean vertical velocity within the rain-belt was -0.08 Pa/s for nCP25-Africa and -0.05 Pa/s for CP4-Africa (negative values represent ascent). The mean net ascent within the rain-belt at 500hPa is the result of a wide distribution of vertical velocities as shown in Figs 15c&d. Explicit convection in CP4-Africa yielded a markedly wider range of vertical velocities than the parameterised convection of P25. The variance of the w500 distribution was greater and very intense vertical velocities, particularly for upward motions, occurred more frequently. In CP4-Africa, ascent at 500hPa was markedly more intense when raining (-0.90 Pa/s) than for parameterised convection in nCP25-Africa (-0.25 Pa/s).

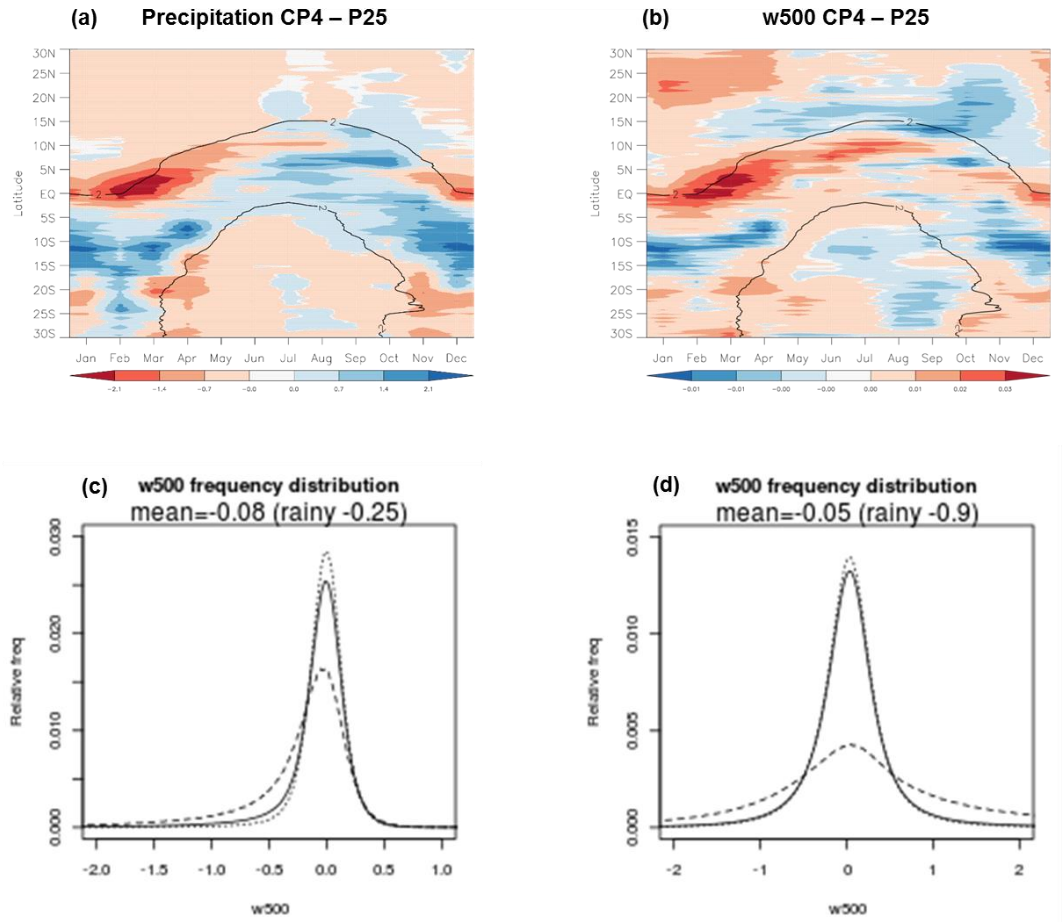


Figure 15: Current climate simulations based on 10 years' data for nCP25-Africa (P25) and CP4-Africa (CP4). (a) The difference in monthly mean zonal precipitation for CP4 less P25 (mm/day). (b) The difference in monthly zonal mean vertical pressure velocity at 500hPa for CP4 less P25 (Pa/s). Red shading represents weaker ascent and blue shading represents stronger ascent. (c) The frequency distribution of 3-hourly instantaneous w500 for P25. The solid line represents all events, the dashed line rainy times only, and the dotted line dry times. The units for w500 are Pa/s. (d) As (c) but for CP4.

Provisional results for future climate under greenhouse gas warming show that the mean vertical velocity at 500hPa weakened with both parameterised and explicit convection. About the equator in February, mean vertical velocity weakened from -0.08 Pa/s to -0.06 Pa/s in nCP25-Africa and weakened from -0.05 Pa/s to -0.03 Pa/s in CP4-Africa. In contrast, in CP4-Africa, with explicit convection, vertical velocity intensified when raining from -0.9 Pa/s to -1.04 Pa/s. This suggests that the more intense upward motions within the tropical rain-belt intensify with warming. Similarly, heavy precipitation intensified with warming. The intensification of heavy precipitation also occurred in nCP25-Africa but was not coupled with an intensification of convection when raining.

Next steps:
The next step in this work will be to extend the analysis of the relationship between precipitation and the Hadley cell circulation in the tropical rain-belt to include the whole tropical rain-belt over Africa. The key tasks are: first, to complete the evaluation of the precipitation/Hadley circulation relationship for CP4-Africa compared to nCP25-Africa; second, to compare changes in rain-belt width, intensity and depth under greenhouse warming in CP4-Africa and nCP25-Africa; and finally, to quantify the change in overturning circulation of the Hadley cell including the contribution from radiative cooling of the atmosphere in the subsidence regions.

iii. HyCRISTAL – Lake Victoria region

Last year studies showed improved westward propagation of storms in the rift valley in CP4-Africa relative to nCP25-Africa. This year study of the moisture budget over Lake Victoria as well as indices related to land-lake and mountain breezes have been used to understand differences between CP4-Africa and nCP25Africa rainfall over the lake. Observations (TRMM) indicate that during the EASR there is a peak in rainfall over the lake (Fig 16a). CP4-Africa generates too much rainfall over the lake whereas nCP25-Africa generates too little rainfall (Figs 16b and 16c respectively). The higher rainfall in CP4-Africa is associated with larger convergence over the lake overnight and in the early morning. Increased convergence in CP4-Africa appears related to a stronger land-to-lake (lake warmer than land) night time breeze rather than with mountain-valley breezes. The plausible representation of such-mesoscale processes opens up potential to study the impact of climate change on these features using the future idealised simulations.

Although CP4-Africa EASR rainfall totals are too high, the timing of the observed EASR peak month is improved relative to nCP25-Africa. The CP4-Africa peak is in November (the same as observed) whereas the peak month in nCP25-Africa is October. Comparative studies of the models' moisture budgets indicate these differences arises because moisture flux out of the western boundary of the region reduces in November for CP4-Africa, whereas in contrast it increases in nCP25-Africa – reducing available moisture.

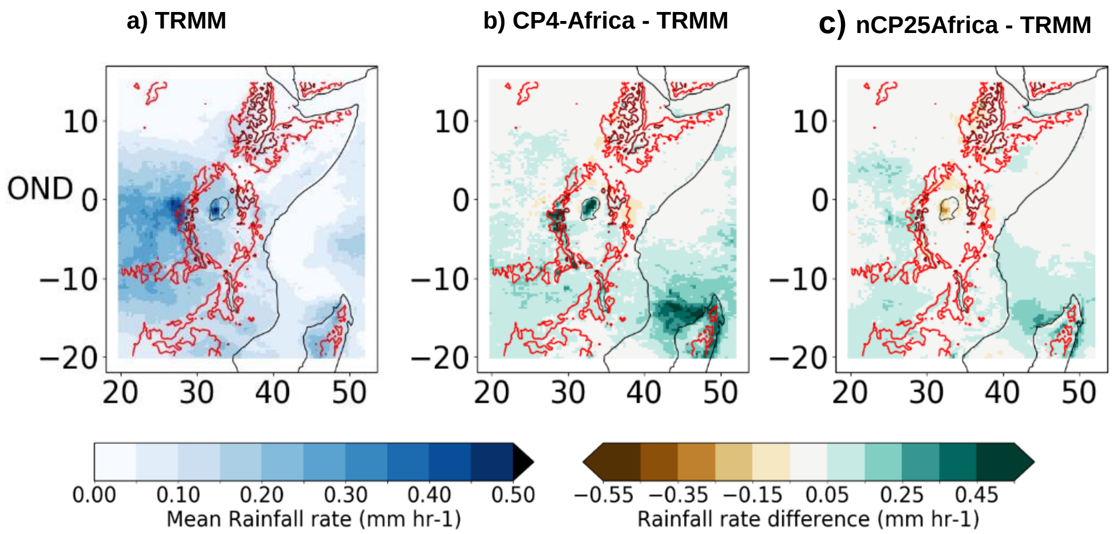


Figure 16: East Africa Short Rains (EASR) season, OND rainfall, a) Observed (TRMM) OND long-term average (mm/hr); b) CP4-Africa minus TRMM; c) nCP25-Africa minus TRMM.

iv. UMFULA – representation of Tropical Temperate Cloud Bands (TTCBs)

Tropical extratropical cloud bands, also known regionally as tropical temperate troughs, are one of the main rainfall systems for subtropical southern Africa during the summer rainfall season.

An object-based algorithm developed for detection of cloud bands in satellite data was applied to the family of MetUM simulations run as part of the FCFA-IMPALA programme. The global (N512 Global) and regional (nCP25-Africa) climate simulations run at a horizontal resolution of N512 (~ 25km) employ convective parametrization, whereas a configuration (CP4-Africa)

with horizontal resolution of ~4.5km is run with the convection scheme turned off since large-convective cells are explicitly permitted at such resolutions.

Our results demonstrate that the CP4-Africa simulation shows a vast improvement in the seasonal cycle of cloud band occurrence when compared to observations. The convective-parametrized simulations are biased to produce too many cloud bands during the winter months, and too few in the summer months (top two panels of Fig. 17): CP4-Africa reduces both the winter and summer biases in cloud band number (lower panel of Fig. 17). This result is summarised by the improved correlation between observed and simulated cloud band seasonal cycles with the r-value=0.88 from CP4-Africa, a substantial improvement from the N512 Global and nCP25 simulations (0.19 and 0.61 respectively).

The climate dynamics underlying this improvement in the simulation of the seasonal cycle are currently the focus of ongoing work in UMFULA. Preliminary results suggest this improvement is a result of the improved ability in CP4-Africa to produce deep convection during the summer months across southern Africa, and associated improvements in the mean structure of upper-level westerly winds across subtropical southern Africa.

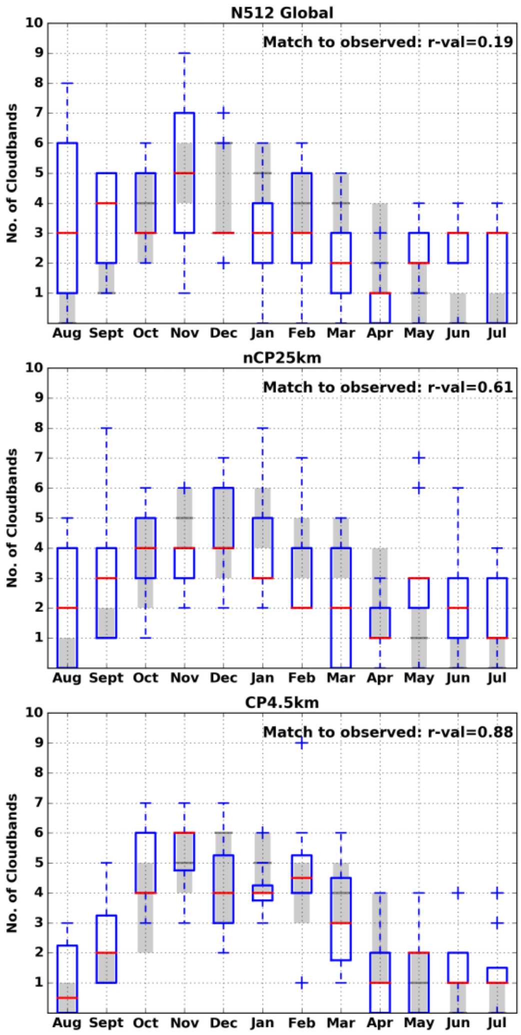


Figure 17: The seasonal cycle of tropical-extratropical cloud bands across southern Africa as simulated by MetUM Global Atmosphere v7 N512 model (top), a regional pan-African 25km model (middle), and a regional pan-African 4.5km convective-permitting model. Grey shaded boxes provide observed interquartile range in cloud band count, with simulated interquartile range indicated in blue boxes. Red line denotes the median cloud band count from the 10-year timeslice simulations. R-val indicates correlation between median observed and median simulated cloud band counts.

W2.2 Land model development

Work this year has continued to be directed towards improving a number of aspects of the JULES model (Joint UK Land Environment Simulator) of particular importance for modelling African climate change, notably canopy interception loss, root zone soil moisture, drought deciduous phenology and photosynthesis. JULES forms the land component of the MetUM and thus improvements will enhance the physical basis of the MetUM climate change predictions.

Highlight results last year included reporting on the dramatic reduction (and more realistic) canopy interception losses in the CP4-Africa model relative to nCP25-Africa. This year investigations into the surface water budget in CP4-Africa and nCP25-Africa have continued and results on drought deciduous phenology are also emerging.

In addition, an investigation on the timescale on which deep saturation of soils return to moisture levels within the typical interannual range has been undertaken. This was prompted by an accidental (and now corrected) reset of soil moisture in CP4-Africa, at all soil levels, to saturation. The investigation aided design of a 1-year corrective "patch" for the CP4-Africa simulations and also provides insights into the working of the JULES representation of soil water balance.

a) Soil recovery from saturation

When the CP4-Africa current climate simulation was reconfigured, having reached 1/7/97, the soil moisture in all levels was inadvertently set to saturation. To assess the impact of this soil moisture reset on the atmosphere, outputs of soil moisture and evaporative fluxes from the soil were analysed. Most of the water added to the soil is lost within subsequent days as subsurface runoff which is lost to the model. The two pathways for water fluxes from the soil to enter the atmosphere are via bare soil evaporation and plant transpiration. Bare soil evaporation peaks on the first day but declines rapidly (after 5 to 6 days) as is it sourced from the top soil level only and is a relatively small reservoir of water. Moisture fluxes via plant transpiration are regulated by the availability of soil moisture and the land cover and is a function of the rooting depth for that plant functional type. The ability to draw water from each soil level also determines how quickly soil moisture levels return to pre-saturation levels but also how long-lasting an impact the reset will have on soil moisture levels in the deepest levels. Overall evapotranspiration returns to within an inter-annual range within six months. Areas with high fractions of deep-rooted vegetation tend to occur in areas of high annual rainfall and consequently, in these regions, both soil moisture in deepest levels and evaporative fluxes return to with an inter-annual range within six months. In areas dominated by shallow rooted vegetation and bare soil, the deep level soil moisture remains elevated for the duration of the simulation, however this has a negligible impact on transpiration beyond 6 to 12 months. A 12-month patching run therefore mitigates the worst effects of the soil moisture reset.

b) Surface water budget

Pan-Africa comparisons of the surface water balance in the CP4-Africa and nCP25-Africa models for the current climate have been computed for the 10 years of simulations (Table 4). Both models show good agreement in the average annual rainfall accumulations over land, although with some spatial variation (Fig. 18 (left)). Figure 19 shows the fraction of rain days per season and illustrate large differences with rainfall almost every day in nCP25-Africa, whilst in CP4-Africa the frequency is reduced to less than one in three days on average. As a result, between 10 and 40 % of annual rainfall is intercepted by the canopy in nCP25-Africa compared to less than 10% in CP4-Africa (Fig. 20). From observations, expected losses are ~13 % for Amazonian forests and 9% at Tai Park in Ivory Coast during August to December

(Hutjes et al., 1990). Whilst interception losses are too high particularly in coastal areas in nCP25-Africa, interception losses are a little too low in the convection permitting model.

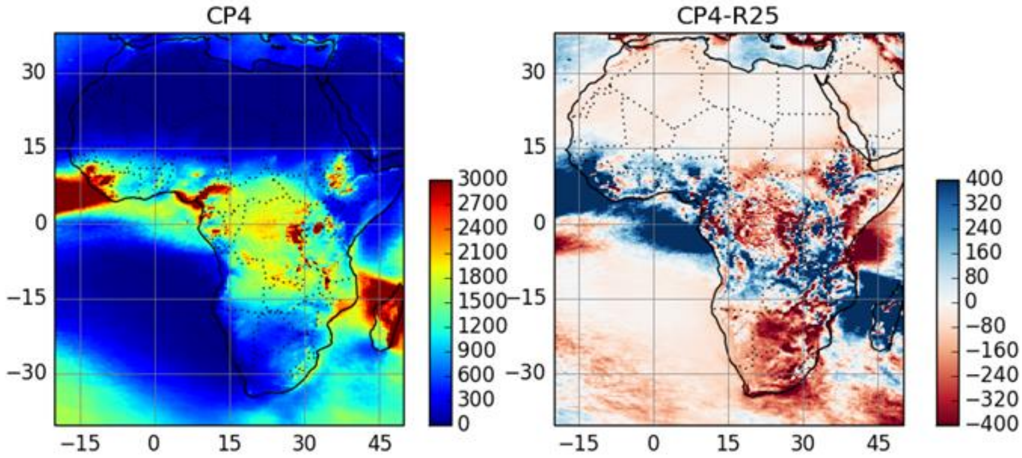


Figure 18: Mean annual rainfall (mm/year) in CP4-Africa (left) and the difference, CP4-Africa minus CP25-Africa (right).

Mm/year (% rain)	Years	Rainfall	Canopy Evap.	Evap. from Soil	Surface Runoff	Subsurface Runoff	ΔSM
CP4-Africa	10	672	31 (5%)	383 (57 %)	190 (28%)	79 (12%)	-10
nCP25-Africa	10	675	107 (16%)	391 (58 %)	133 (20%)	34 (5%)	10

Table 4: The pan-Africa water balance for the current climate for CP4-Africa and nCP25-Africa models in mm/year and (in brackets) as a percentage of annual rainfall.

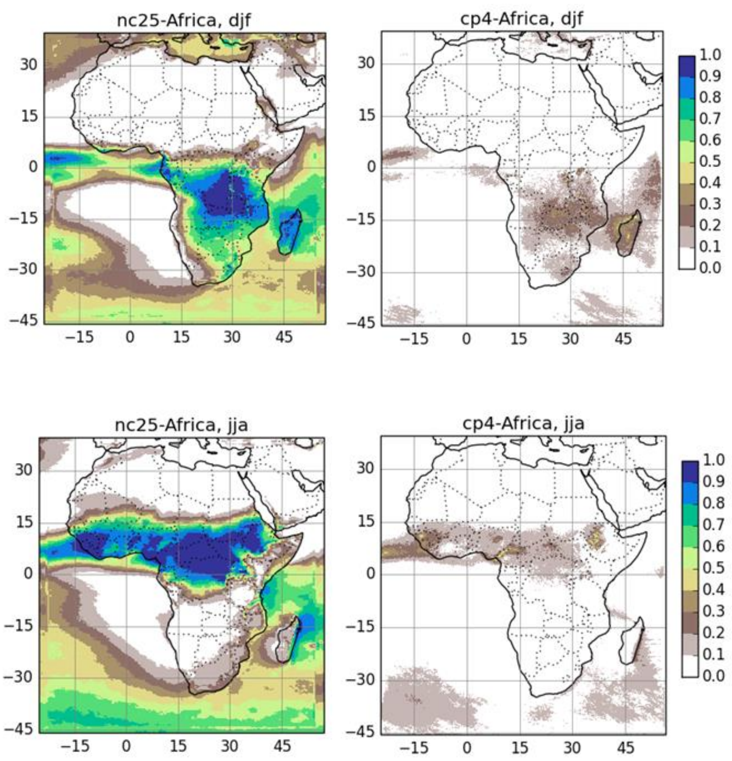


Figure 19: The fraction of days with rainfall above 0.5 mm/day for DJF (top) and JJA (bottom) and for nCP25-Africa (left) and CP4-Africa (right).

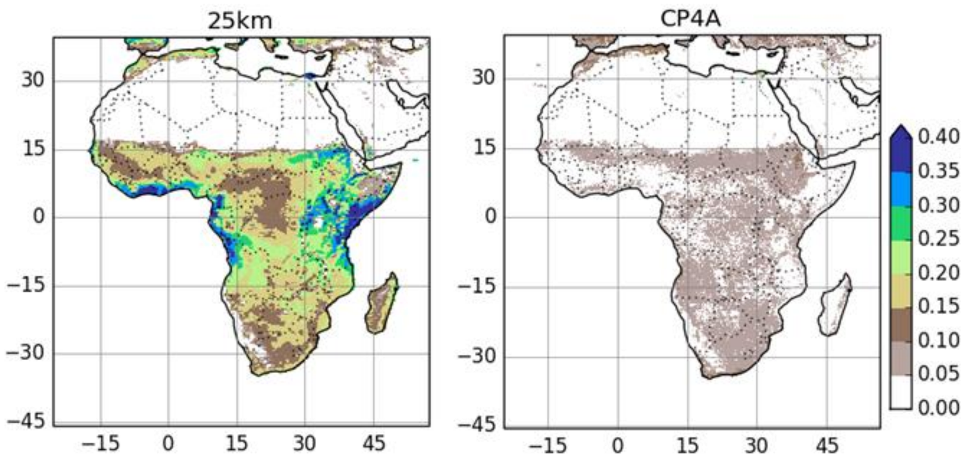


Figure 20: Annual interception loss (as a fraction of rainfall) nCP25-Africa (left) and CP4-Africa (right).

The convection permitting model has a higher proportion of surface runoff and subsurface runoff (Table 4) which is due to more rainfall reaching the surface when rainfall occurs. There is also a difference in the treatment of rainfall entering the land surface of the two models to do with the rainfall area. In the large-scale model the rainfall area fraction is allowed to vary whereas in the convection permitting model the rainfall area fraction is fixed at one. This means that for a lower rainfall area the same intensity rainfall produces faster surface runoff and lower infiltration of water into the soil. This difference will contribute to the higher values of sub-surface runoff seen in CP4-Africa.

Annual evaporation from the soil is similar in both models, however seasonal differences are present (Fig. 21). In particular at ~10N to 15 N where annual rainfall is similar but CP4-Africa has higher dry season (SON) evaporation. Work is ongoing to understand the impact this has on the sensible heat flux, air temperatures and low-level circulation.

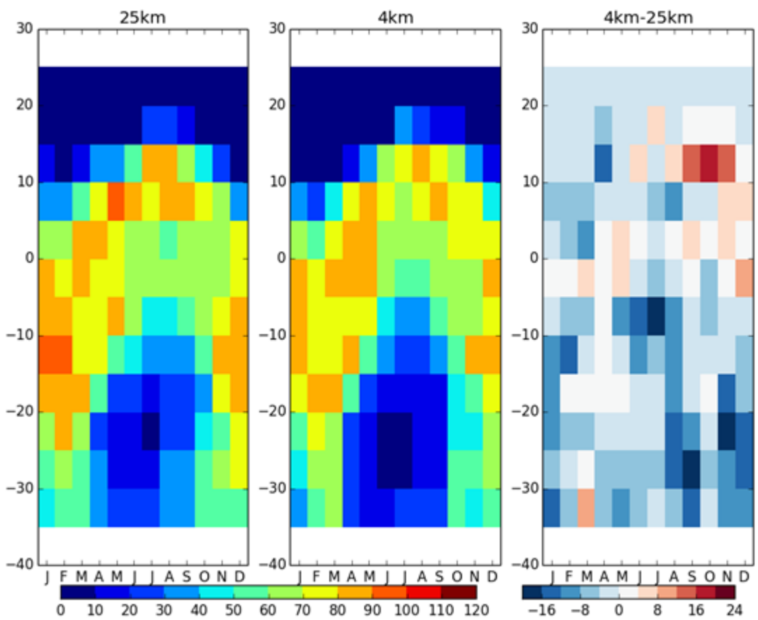


Figure 21*:* Zonal means (-15 to 45 E) of evaporation from the soil (mm/month) for the parameterised nc25-Africa (left) and convection permitting (middle) models and their difference, CP4-Africa – nCP25-Africa (right).

c) African grassland phenology: Sensitivity of JULES modelled LAI to soil and root parameters

Land surface characteristics affect surface energy, moisture and carbon fluxes that influence a wide range of meteorological processes. Across tropical regions, moisture fluxes in particular can exert a strong control on the initiation and propagation of convective systems which dominate local, diurnal rainfall (Pielke, 2001), as well as larger and longer scale moisture budgets and synoptic patterns (Spracklen et al., 2012; Taylor, 2008). Nowhere are these effects more evident than over Africa (Koster et al., 2004; Taylor et al., 2012), where large spatial and temporal moisture gradients transform the land surface. Capturing realistic responses of land surface properties (soil moisture, vegetation leaf area) and fluxes to tropical rainfall variability is very challenging, yet this response is important for simulating climate variability and change over Africa.

In this part of IMPALA work to assess and develop the JULES land-surface model we are evaluating the sensitivity of African vegetation phenology (timing of seasonal events i.e. start of season, peak of season), modelled using JULES, to variations in model parameters, particularly those that are likely to affect the drought-deciduous response. Improving this response will allow the model to better simulate intra-seasonal and inter-annual vegetation anomalies that are related to rainfall variations, permitting a more accurate feedback with the atmosphere on time scales of weeks to months.

Results presented here compare the seasonal cycle of modelled Leaf Area Index (LAI), using a range of parameter settings in JULES (Table 5), with satellite-derived LAI from the Copernicus Global Land Service (GLS) product.

Parameter	Brief description	Settings used
fsmc_mod_io	Switch for method of weighting the contribution of soil layers to the soil moisture availability factor, fsmc. 0 - Calculates average fsmc for the soil column by weighting each soil layer by the fraction of roots in each layer. The root distribution e-folding depth is given by the parameter rootd_ft_io. 1 – Calculates average fsmc for the soil column using average root distributions. The depth of root zone is given by the parameter rootd_ft_io.	0, 1
rootd_ft_io	Root zone depth profile. If fsmc_mod_io=0, an exponential root distribution, e-folding depth is assumed. If fsmc_mod_io=1, total depth of roots extend to the value provided.	0.5, 0.65 (for fsmc_mod_io=0) 0.5, 3.0 (for fsmc_mod_io=1)
dgl_dm_io	Rate of change of leaf turnover rate with moisture availability.	0, 0.5, 30.0 (varying with Plant Functional Type)

Table 5: JULES parameters and settings used to test the seasonal sensitivity of modelled LAI

LAI is an estimate of the total leaf area (one sided) in a vegetation canopy per unit ground area, and therefore provides an indication of canopy density. The GLS satellite LAI product (versions 1.4 and 1.5) utilises observations from the SPOT-VGT and PROBA-V sensors, averaged to a 1 km spatial resolution (see https://land.copernicus.eu/global/content/product-quality-lai-1km). These data are available from 1999 to present and have been shown to exhibit good spatial and temporal consistency (Camacho *et al.*, 2013). Version 4.6 of JULES was used for the simulations, with 9 Plant Functional Types (PFTs, see Table 6) and settings to enable the model to estimate LAI based on the dynamics of vegetation productivity and

competition[3]. The runs had a global grid spacing of ~135 km (N96), land cover fractions were defined through time based on HYDE (Klein Goldewijk and van Drecht, 2018), and the driving climate data were from the NOAA-NCEP reanalyses.

PFT short name	PFT long name
BET-Tr	Broadleaf Evergreen Tree - Tropical
BET-Te	Broadleaf Evergreen Tree - Temperate
BDT	Broadleaf Deciduous Tree
NET	Needleleaf Evergreen Tree
NDT	Needleleaf Deciduous Tree
C3	C3 Grass
C4	C4 Grass
ESh	Evergreen Shrub
DSh	Deciduous Shrub

Table 6: The 9 Plant Functional Types (PFT) modelled in JULES simulations

Here, we present results focused on grasslands and savanna across Africa, using the World Wildlife Fund (WWF) biomes map to identify current grassland and savanna areas, and separating broadly similar climate zones using 'Giorgi' climate regions (Giorgi and Franciso, 2000), (Fig. 22).

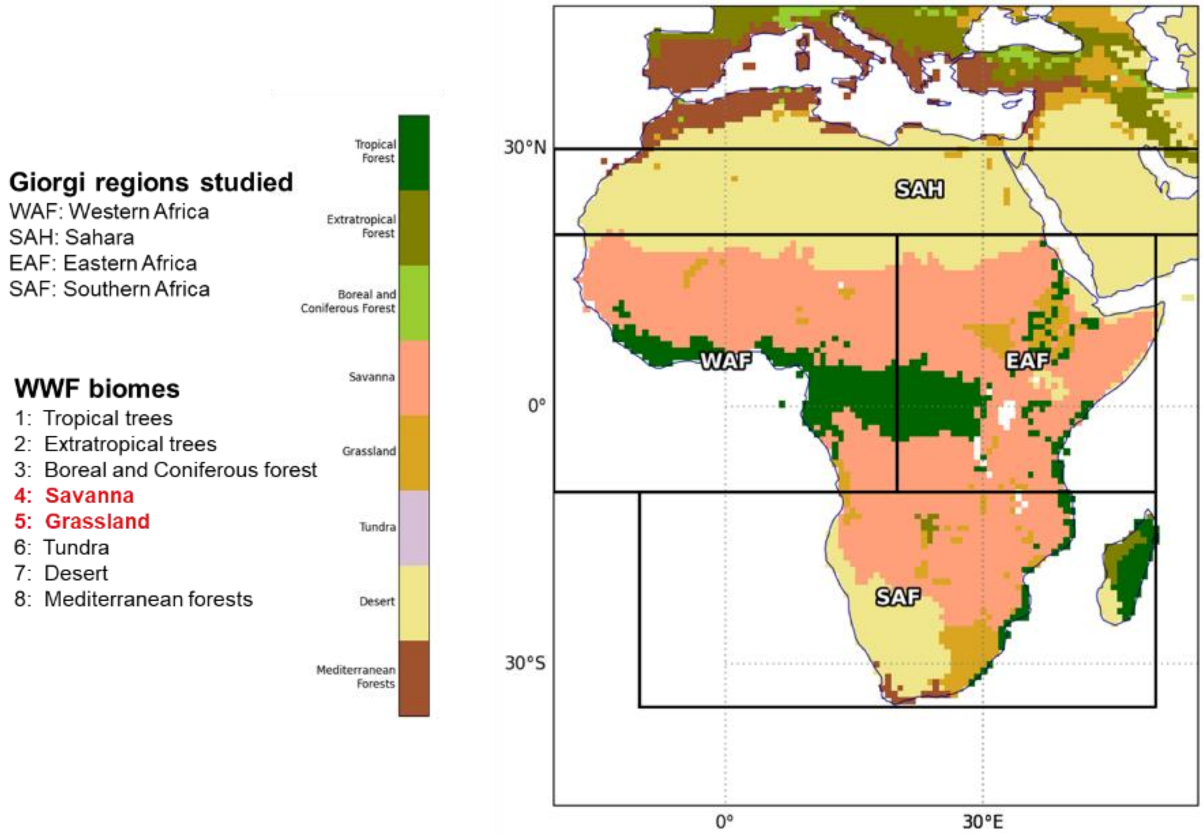


Figure 22: Map of World Wildlife Fund (WWF) biomes, and the 4 'Giorgi' climate regions referred to in the text

The following results describe the LAI averaged by WWF biome (either grassland or savanna) within a specified Giorgi region. Figure 23 highlights some of the key features of different

[3] Details of the model configuration can be found in the rose suite: u-ah655

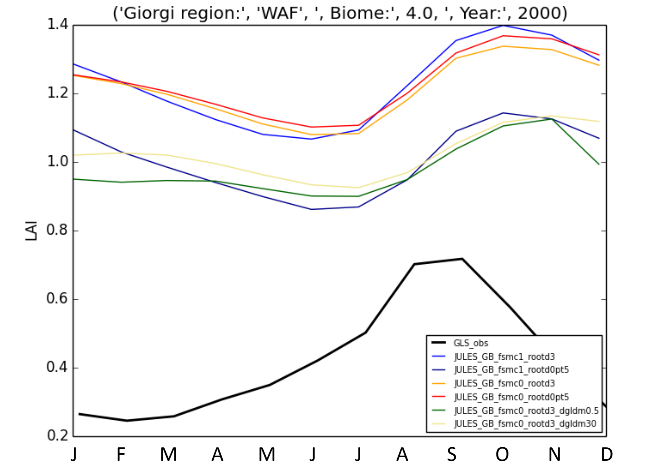
modelled seasonal cycles of monthly-average LAI with varying JULES parameters (as detailed in Table 5), relative to the corresponding GLS LAI product.

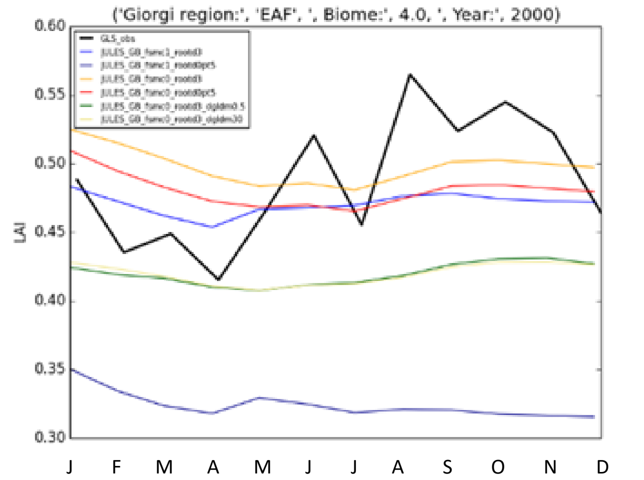
For some locations, the timing and magnitude of the modelled seasonal cycle of LAI are improved by including a moderate rate of change in leaf turnover rate with moisture availability (dgl_dm_io between 0.5 and 15.0). An example of this can be seen in Fig. 23 for South African grasslands in 2000, where the observed decrease in LAI from around 2.0 in January-March to 0.5 in July-August is influenced by corresponding reduced precipitation during the summer month, which is only captured in JULES when the leaf turnover rate is associated with moisture availability through the dgl_dm_io parameter. However, for other regions and biomes the association between LAI and dgl_dm_io is less clear, e.g. grasslands in WAF and EAF during 2000 (Fig.23, upper graphs).

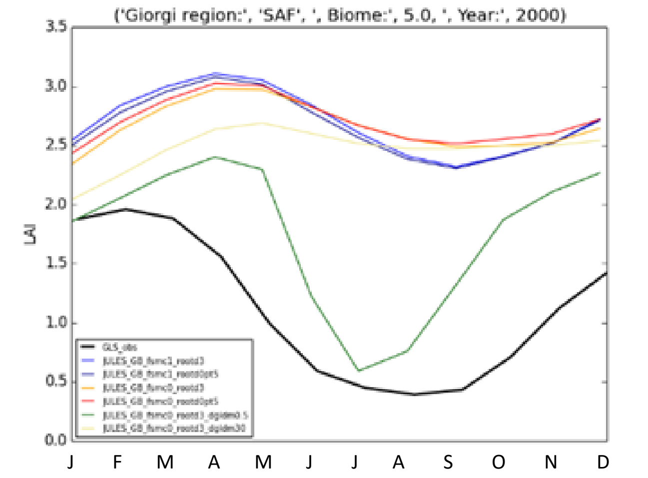
Next steps

Further sensitivity tests are underway, and these results will be combined to provide recommendations for improving parameterisations for further model runs. The aim is to include these in coupled GCM/ESM model runs and evaluate their influence in terms of e.g. seasonal responses and feedbacks of the land-atmosphere system to remote forcing.

Work assessing the JULES land-surface model will continue and contribute to a comprehensive end of project assessment. The response of land surface temperature during dry spells will be evaluated across CMIP5 models.







Different colour lines represent the GLS satellite data (black), and JULES model data with the following parameter settings:
fsmc_mod_io=1 & rootd_ft_io=3 (royal blue),
fsmc_mod_io=1 & rootd_ft_io=0.5 (dark blue),
fsmc_mod_io=0 & rootd_ft_io=3 (orange),
fsmc_mod_io=0 & rootd_ft_io=0.5 (red),
fsmc_mod_io=0 & rootd_ft_io=3 & dgl_dm_io=0.5 (green),
fsmc_mod_io=0 & rootd_ft_io=3 & dgl_dm_io=30.0 (yellow).

Figure 23: Seasonal cycle (monthly averages) of LAI during 2000, averaged across the savanna (biome 4) and grassland (biome 5) WWF biomes within the West Africa (WAF – upper left), East Africa (EAF – upper right) and South Africa (SAF – lower) Giorgi climate regions. See inset for colour coding.

4.3 WP3: Metrics and Model Evaluation

WP3.1/3.2/3.3: Review of suitable metrics; preparation of assessment tools and model evaluation

WP3 research is funded for year 1 and year 4 of IMPALA. The main aim for year 1 was to evaluate the performance of the "baseline" MetUM at the start of IMPALA (HadGEM3-GC2), with different researchers focusing on different regions: Babatunde Abiodun (West Africa), Ben Lamptey (West Africa), Joseph Mutemi (East Africa), Wilfried Pokam (Central Africa), Rachel James (southern Africa), and Gillian Kay (pan Africa). Due to contracting delays at the beginning of the project, it was opportune to carry over this work to year 2, and 2016 saw great progress, with evaluation for all regions, a workshop in Oxford, and the completion of a paper which has now been published in *BAMS* (James et al. 2017)

Further progress this period, includes:

- revision and publication of the *BAMS* paper;
- the *BAMS* paper presented at the IAMAS conference in Cape Town in August 2017 (oral presentation by Rachel James) and AMS conference in Austin in January 2018;
- progress on the concept of the model evaluation hub and refining ideas on how to initiate it, including through a breakout group at the FCFA conference in Cape Town in September. As a result, letters introducing this initiative are now being sent to a wide range of experts in African climate modelling (including the CORDEX community);
- As part of the FCFA webinar series, IMPALA/UMFULA researcher Rachel James gave a webinar on the BAMS paper and the concept of the evaluation hub, "How can climate models be improved over Africa? Investigating global models with local knowledge";
- WP3 meeting at the FCFA conference;
- the recruitment of 6 ECRs to the WP3 team (see Section 2, Table 1)

Further evaluations of the MetUM have been undertaken by the core Africa-based researchers and ECRs – see next subsections.

- analysis of temperature and precipitation climatology in GC2 over West Africa (Thompson Annor);
- analysis of GC2 moisture and rainfall climatology over East Africa (Joseph Mutemi, Anthony Mwanthi);
- analysis and planning for a paper focusing on drought over West Africa, led by Babatunde Abiodun;
- analysis of jets and vertical velocity over Central Africa by Wilfried Pokam;
- further analysis of TTTs over southern Africa by Rachel James (see below);

a) Progress with the evaluation over southern Africa (see also Section 4.2c)

During year 1 & 2, tropical-extratropical cloud bands, or "Tropical Temperate Troughs" were analysed in GC2 and compared to satellite data. This was published in James et al. 2017. During year 3, part of the UMFULA analysis was to investigate TTTs over southern Africa in CMIP5. GC2 has been included alongside CMIP5 models in this analysis, leading to some new findings relevant for IMPALA.

The initial work in year 1 and 2 made use of a cloud band identification software developed by Hart et al. (2012) to investigate the number, spatial distribution, and seasonal cycle of TTTs, as well as the relationship with precipitation. This showed that GC2 produces TTTs with a similar spatial distribution to satellite data, however, the number of TTT events is too high, especially over the Indian Ocean. It also produces too much rainfall associated with TTTs, and this partly explains the model's wet bias over the region.

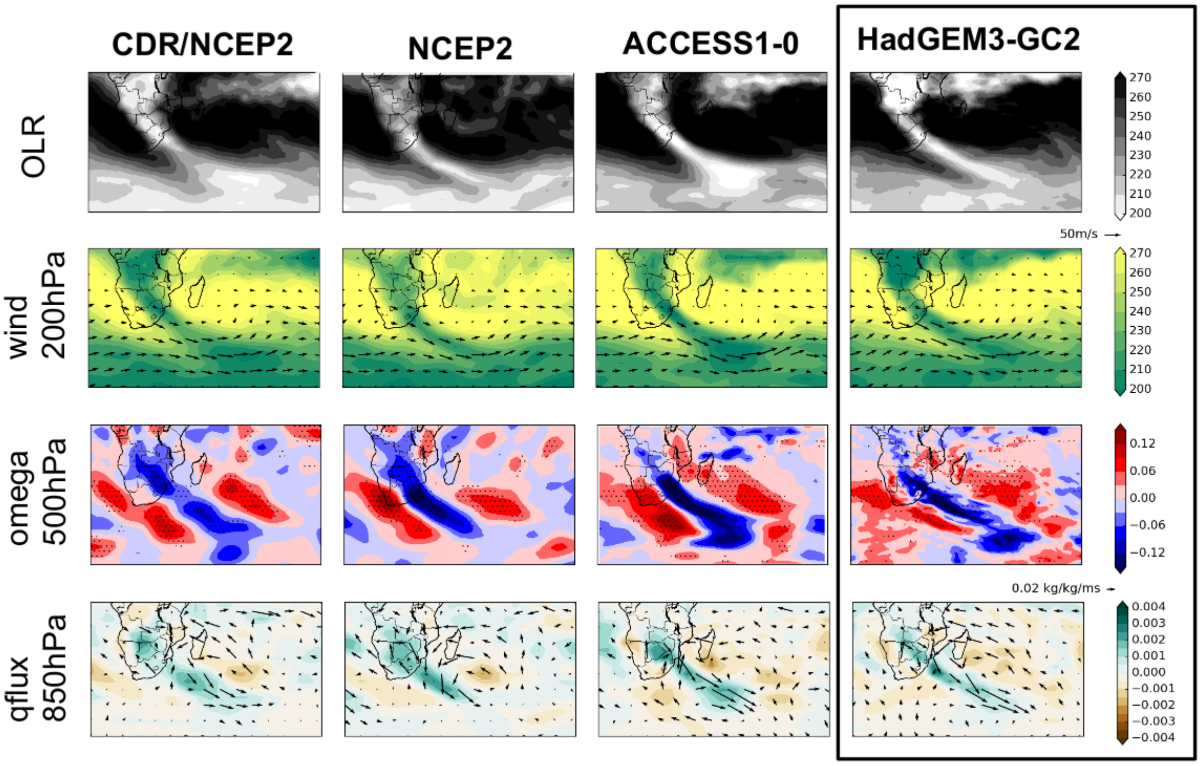


Figure 24: Circulation associated with composites of 10 TTT days from satellite data (NOAA CDR), reanalysis (NCEP2), one CMIP5 model (ACCESS1-0), and HadGEM3-GC2. The rows show (i) the composite outgoing longwave radiation (OLR) with a cloud band extending in a north-west to south-east direction over the continent, (ii) a wave in the 200hPa westerly winds, with the OLR shown in green for reference, (iii) a ridge-trough-ridge as shown in omega at 500hPa, with stippling to indicate agreement across the composite, (iv) specific humidity (shading) and moisture flux (vectors) at 850hPa, demonstrating south-eastward moisture flux.

In 2017 the analysis focused more on the dynamics of TTT events, to investigate the regional circulation associated with tropical-extratropical cloud bands and compare this between models and reanalysis. The results show that the structure of TTT events in models, including GC2, is quite similar to reanalysis. TTTs are associated with a wave in the upper level westerly winds, a ridge-trough-ridge structure with a wave-train approaching from the southern Atlantic Ocean in the preceding days, and a south-eastward export of moisture (Fig. 24).

Next steps

Whilst the models show similar regional circulation associated with TTT events, there are differences in the intensity, as well as the preferred location and timing of TTTs. The next step in the UMFULA analysis is to investigate how and why there are differences in the statistics of TTTs, despite similar dynamics. This will inform an assessment of the extent to which models (including GC2) can be trusted to represent southern African climate.

b) Evaluation of UM over Central Africa

This sub-section presents progress in metric analysis over Central Africa (CA), with focus on the second and main rainy season from September to November (SON). Previous Unified Model (MetUM) bias analysis during this season highlighted a strong wet bias over eastern CA associated with overestimation of vertical motion in the MetUM over this area. Then, investigation of drivers of vertical motion over CA may help to define metrics to understand the MetUM precipitation bias.

Previous studies (e.g. Jackson et al 2009, Nicholson and Grist 2003) support that strong convection over CA during SON is related to the well-developed northern and the southern branches of the African Easterly Jet (AEJ) during this season. Therefore, this report aims to present insights into mechanisms associated with the development of AEJ components: the associated ageostrophic circulation and in turn the link to vertical motion. The approach used here is to access the contribution of both branches of AEJ to the vertical motion over CA using reanalysis. Identified mechanisms are used to define metrics for understanding of vertical motion and precipitation biases in the MetUM over CA.

Insights into AEJ components show that they are modulated by the lower level meridional temperature gradient. The northern component of AEJ (AEJ-n) results from contrast in lower level temperature between cold Congo Basin and warm Sahelian zone in the north. Whereas the southern component of AEJ (AEJ-s) forms when there is a strong contrast in surface temperature between the cold Congo Basin and warm area over southern Africa. Analysis shows that both AEJ-n and AEJ-s are located at mid-level over a low-level peak in the meridional gradient of potential temperature, slightly equatorward of these peaks.

Analysis of level-latitude section of wind divergence reveals that between the jet components (over CA) there is prevalence of mid-level convergence and weak divergence at lower level. Poleward of the core of each jet component, there is a divergence centre underneath by near surface wind convergence centre. This divergent structure is driven by the ageostrophic circulation which modulates a transverse circulation associated to the jet components. Between the surface and the mid-level, the transverse circulation promotes upward motion poleward of AEJ-n and AEJ-s and descent over CA. This is well observed in the meridional circulation of ageostrophic wind. There a good agreement between reanalyses in this jet streak structure (Uccellini and Johnson, 1979) associated to both AEJ-n and AEJ-s.

Ageostrophic circulation associated to both AEJ-n and AEJ-s has positive and negative effects on the development of convection during main rainy season in SON over CA. Ageostrophic circulation contributes to mid-level convergence during this season and then supports the development of convection (Jackson et al 2009). At the same time, subsidence between mid to lower level associated with the ageostrophic transverse circulations may play as a damping effect on convection over the region. Therefore, assessment of the location and the strength of AEJ-n and AEJ-s appear as good metrics to evaluate vertical motion bias in UM.

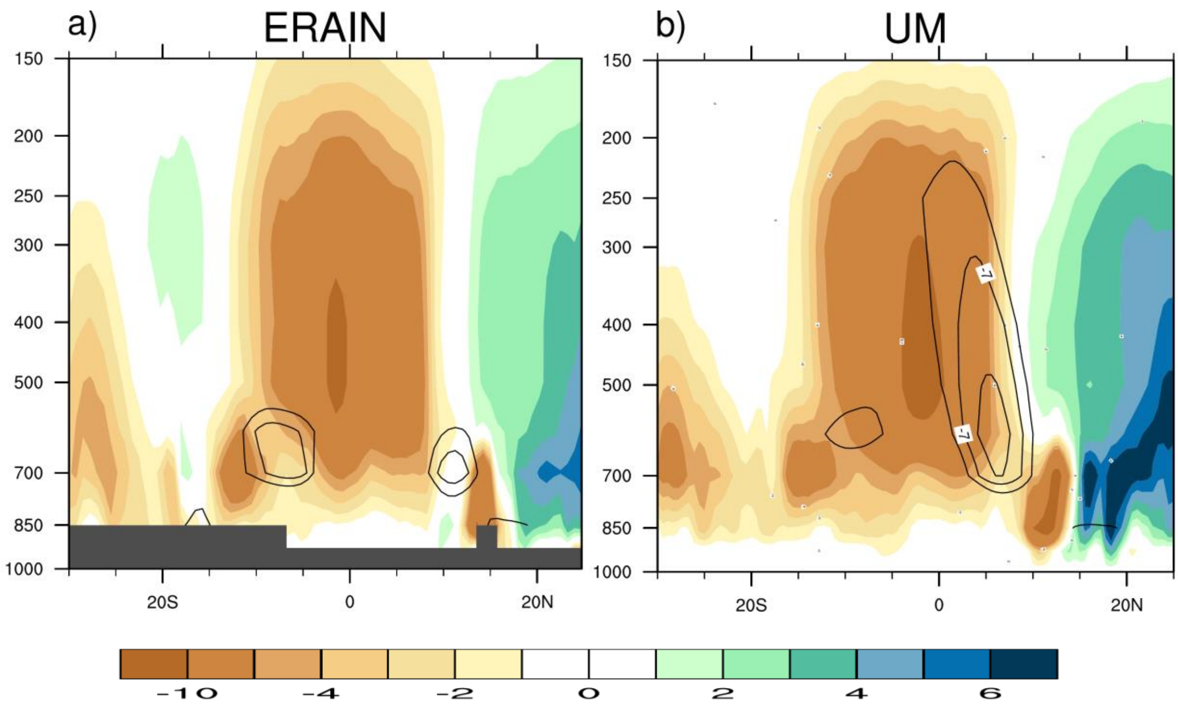


Figure 25: Mean monthly vertical motion (shading) and zonal wind (contours) for October, averaged between 20^{0}E and 28^{0}E over Central Africa. Only contours of easterlies stronger than 6 m.s^{-1} are represented to show core speeds of AEJ-s and AEJ-n, a) ERA-Interim, b) MetUM

Figure 25 shows the mean meridional vertical motion in ERAIN and MetUM. It is evident that the vertical motion is stronger in MetUM compared to ERAIN. The core of vertical motion between the equator and 5^{0}S, and 400-500 hPa, is stronger in the model. A striking feature is the weakness of AEJ-s in the MetUM suggesting that a stronger ageostrophic circulation associated with the jet component in ERAIN compare to the model. Then, the negative effect of the transverse circulation associated with AEJ-s is weaker in the model compared to the reanalyse. This leads to strong vertical motion over Central Africa in MetUM, mainly south of the equator.

Moreover, there is a more equatorward location of both components in the MetUM compared to ERAIN. This feature and the underestimation of the strength of AEJ-s suggest that the surface conditions (gradients) that drive the jets are not well represented in the model. This contributes to a poor representation of the contribution of the jet components in the vertical motion in the MetUM compared to ERAIN, and in turn to the wet bias in the model over western Central Africa in SON.

Diabatic heating contributes ageostrophic circulation. Further investigation will focus on understanding this interaction between diabatic heating and vertical motion over Central Africa. This may help to enhance insights into the ageostrophic motion and in turn better understand vertical motion drivers over the region. Detailed investigations of surface conditions over Central Africa in UM are also needed. These analyses are important to explore precipitation bias in the MetUM over Central Africa.

c) West African Precipitation and Temperature climatology: An Evaluation of the Unified Model on Annual, Seasonal and Monthly time scales

Summary
The ability of any climate model either global or regional in reproducing present-day climate fields is very important for the projection of the future state of the same fields. The West African region is a climate sensitive region since most of the sectors of the economies are controlled by the natural climatic processes and therefore the projection of future climate of this region is very crucial. It is against this background that the performance of the MetUM has been evaluated over the West African region over two climatological periods (1979-2000 and 1981-2010) for annual, seasonal and monthly tendencies for precipitation and near surface temperature. While a dry bias is simulated for precipitation especially over the Saharan regions by the model for most of the three timescales, in the case of near surface temperature, a warm bias is produced by the model over the same regions. The performance of the MetUM in reproducing the observed near surface temperature is better than for observed precipitation for most of the time scales over all zones. The MetUM's performance in reproducing both observed temperature and precipitation is best over the Guinea Coast of the West African region.

Introduction
Atmospheric, land surface and ocean fields from GCMs are important forcing data for Regional Climate Models (RCMs) that are in turn used to drive impact studies models. The horizontal resolution of most GCMs are coarse and therefore the representation of subgrid features that are key to the simulation of certain processes like local circulation, topography, precipitation amount and intensity (Jung and Kunstmann 2007; Vigaud et al. 2011; Berg et al. 2013) is low. On the other hand, it has been documented that to a reasonable extent, GCMs are able to capture larger-scale spatial features and processes at longer time scales than RCMs (e.g. Torma et al. 2015; Annor et al. 2017). It is therefore important to assess the strengths and the weaknesses of every GCM that is used for climate studies and the UM is not an exception. Furthermore, it becomes more important to assess how the UM reproduces the climatology of the West African region which is a climate sensitive region. Thus, the aim of this work is to evaluate the UM in reproducing the West Africa precipitation and temperature climatology on annual, seasonal and monthly time scales.

Method
Precipitation and near surface temperature outputs of the MetUM were extracted for periods 1979-2000 and 1981-2010 to compared with the Global Precipitation Climatology Centre (GPCC) version 7 (Schneider et al. 2015) for precipitation and the Climate Research Unit (CRU) version ST-3.2.1 (Harris et al. 2013) for temperature. Spatial biases over West Africa between the MetUM output and the gridded observation data sets were computed for total precipitation and mean temperature over monthly, seasonal and annual periods. The ability of the UM to reproduce the temporal patterns, variability and error for the four seasons (winter, spring, summer and autumn) over the whole West African region was assessed for both precipitation and near surface temperature. The GCM was also evaluated on how it simulated the period monthly mean of annual cycle of both parameters over the whole West Africa and the four regions/zones namely: the Guinea Coast (GC), the Soudano-Sahel (SS), the Sahel (SH) and the Sahara (SA) found within West Africa.

Results
The result for the annual total in precipitation shows relative biases from -90 to 40% with mean bias of -37% for the period 1979-2000 and -41% for 1980-2010 over West Africa with strong dry bias (about -90%) mainly over Niger and western parts of the north of the region for both periods. Apart from these areas, biases are slightly dry elsewhere with the model simulating nearly zero bias over northern Cote D'Ivoire. For annual mean temperature the model

simulated mainly cold (warm) bias over the northern (southern) parts of the domain for both periods.

There are strong wet biases (over 200%) over the northern parts of the domain for the winter and the spring seasons, with the southern portions showing a weak dry bias for both periods (Fig. 26). For the summer season, underestimation of precipitation is simulated over almost the entire domain for both periods. It is only in the autumn season where the MetUM simulated different biases over the two periods: a wet bias for the 1979-2000 period and a dry bias for 1981-2010 period. For temperature (not shown), cold (warm) bias is simulated mainly in the northern (southern) part of the region for both winter and spring seasons with both periods, however, the MetUM reproduced the observed temperature well over the middle portions of the domain. Warm bias (from 0 up to 5 K) is simulated across the entire domain for summer in both periods. In both periods strong warm bias is simulated over northern parts of the region for autumn, the observed temperature is reproduced well along the Guinea Coast.

The unimodal pattern of the annual cycle of monthly mean precipitation averaged over the whole West African region is well captured by the model; however, biases (which are negative) are quite large especially for the rainy season months. In the case of temperature, the bimodal pattern of the annual cycle of the monthly mean temperature averaged over the whole West African region is poorly captured and biases (which are mostly positive) are quite large for most of the rainy season months.

Summary

In general, the MetUM underestimates precipitation across most of the three time scales and this underestimation is resulting from substantial underestimation of rainy season months' precipitation especially over SS, SH and SA regions. Temperature is generally overestimated by the MetUM for most of the three time scales which is resulting from substantial overestimation of rainy season months temperature mostly over SS, SH and SA. In general, the performance of the MetUM in reproducing the observed temperature is better than precipitation for most of the time scales over all zones. The MetUM performance in both temperature and precipitation is the best over the Guinea Coast.

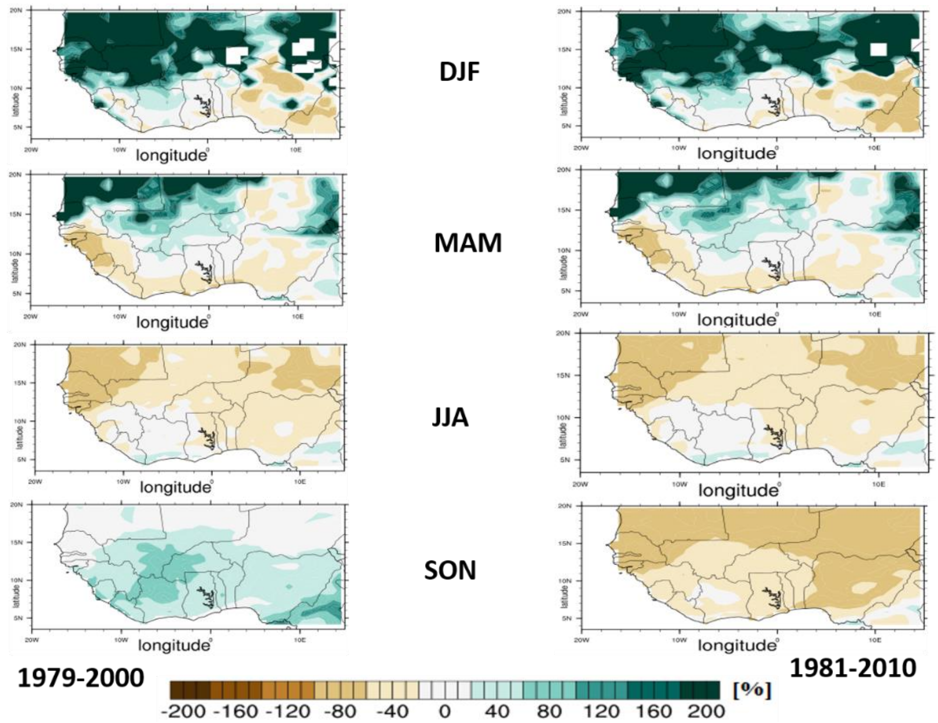


Figure 26: MetUM precipitation biases over West Africa for, top to bottom the DJF, MAM, JJA and SON seasons and for two analysis periods 1979-2000 (left), 1981-2010 (right)

d) East Africa: evaluating representation of low-level moisture in the MetUM for seasonal rainfall extremes in East Africa

This update provides an evaluation of Unified model performance that aids in understanding the model representation of the dynamical processes that can yield extreme weather events. Specifically, rainfall, moisture; vertical and spatial distribution, omega and wind patterns are used in the diagnostic work. The MetUM simulations are evaluated against ERA-Interim reanalysis for selected case study seasons: MAM 2011 (dry) and OND 1997 (wet).

The results indicate that the MetUM rainfall for both MAM and OND climatology is spatially consistence with the ERA Interim reanalysis. However, notable dry biases over central Kenya to southern Somalia and central Tanzania are evident during the MAM season. Consistent with this observation, the vertical moisture integration within the 850-600mb atmospheric column indicates a dry bias especially over southern Ethiopia and South Sudan. For both seasons, the large-scale circulations driven by the sub-tropical anticyclones are generally well-captured.

Our thrust of MetUM evaluation in East Africa is to focus on understanding moist processes that can give rise to extremes in rainfall. From examining the moist depth along a vertical-zonal transect along the equator from 0E to 100E reveals that for wet conditions the moist depth can be as high as 450hPa while for dry conditions, it can be as low as 700hPa for the long rainfall season March-May (MAM). For the short rainfall season, similar results are not evident, indicating that the moist depth is a bit shallower.

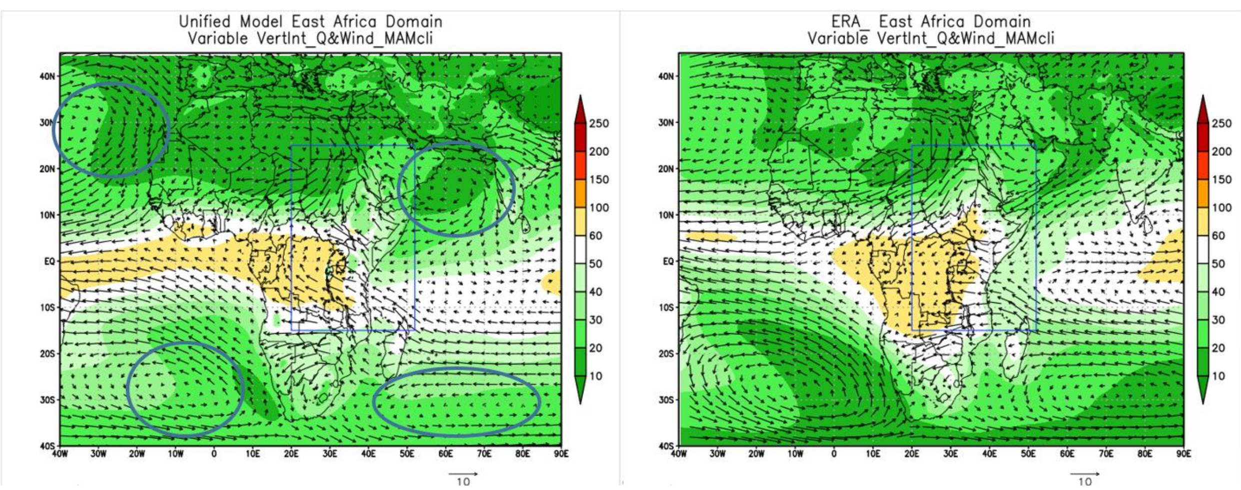


Figure 27: Integrated mean MAM integrated moisture content 850-600hpA (shading) and 850hPa mean (arrows) for the MetUM (left) and ERA-Interim (right). Note easterly flow in the MetUM (left) across equatorial Africa into Central Africa and the Gulf of Guinea. There should be a weakening (or reversal) of easterly flow in the vicinity of the Lake Basin regions of East Africa (as is more evident in ERA-Interim). The flow associated with the subtropical anti-cyclones is highlighted.

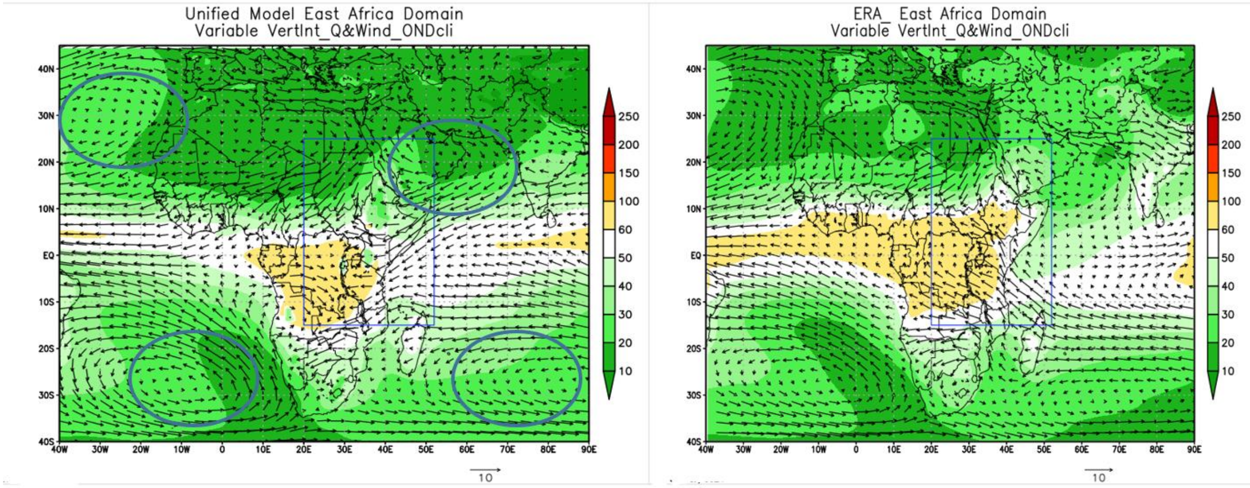


Figure 28: As Fig. 27, but for the OND season. Note the lower column moisture in the MetUM in East and Central Africa, including east of Lake Victoria.

Based on analysis of several atmospheric depths for the MAM climatology, results indicate that most atmospheric moisture during the long rains is largely within the 850-600mb depth, and we thus use this depth in the analysis. The circulation patterns indicate a dominance of easterlies reaching through East Africa to the Gulf of Guinea region (Fig. 27). This implies that the model is somewhat capturing the atmospheric thermodynamics.

For the OND rainfall climatology, a wet bias is observed over much of the western part of the East African domain. Moisture content in the 850-600mb level indicates an under-estimation in the MetUM during the short rains (Fig. 28). For both the MAM and OND climatology, synoptic scale systems such as the anticyclones are captured in the MetUM, hence implying that the model is sufficiently capturing the large-scale drivers of climate. Further analysis will be done to evaluate how the model captures the position of the ITCZ, which is a major synoptic system bearing the bi-modal rainfall over East Africa.

For the selected case studies of MAM 2011 and OND 1997, the rainfall results have a dominant wet bias over East Africa. In both cases, the MetUM is much moister than ERA-Interim for the 850-600mb atmospheric depth. In terms of the wind patterns, MAM 2011 reanalysis have a stronger easterly flow as compared to the model while in the OND 1997 case study, there are no notable differences.

It is thereby concluded that the UM model shows synoptically consistent synoptic scale circulation patterns. However, substantial biases are evident in the regional/local scales. Further analysis is required to gain insight into the causes of these model biases.

Next steps for WP3

The main focus of the IMPALA WP3 work for year 4 is to evaluate the proto-GA8/GC4 version of the MetUM which includes science inputs from WP1 and WP2 (notably the prognostic convective entrainment).

4.4 WP4: Integration and Characterisation of model improvements and implication for future climate change

WP4.1 Model Integration and Improvement

Last year work has focussed on assessment of the impact of model changes incorporated into version GA7 of the MetUM. It was found that dry biases in precipitation are slightly improved at GA7 relative to GA6 particularly in the high resolution (N216) version. Additionally, an in-depth case study of the MetUM representation of African Easterly Waves (AEWs) including use of a new diagnostic tool based on potential vorticity tracking was in progress.

This year the prognostic convective entrainment improvement to the MetUM convection scheme has been pulled through into version proto-GA8/GC4 and further convection improvements (e.g. scale awareness) are undergoing tests for GA9/GC5. Additionally, the research on AEWs has now been published (Tomassini et al 2017) and is summarised below – with brief details of continuing research.

African Easterly Wave case study

In order to support future model development and improve the understanding of the coupling between convection and dynamics, our investigation of the interaction between moist convection and the atmospheric circulation in African Easterly Waves (AEW) was continued. A paper was published in 2017 (L. Tomassini, D. J. Parker, A. Stirling, C. Bain, C. Senior, and S. Milton (2017), The interaction between moist diabatic processes and the atmospheric circulation in African Easterly Wave propagation, Q. J. R. Meteorol. Soc., doi: 10.1002/qj.3173). In the study it is shown that organised convection occurs mainly at and slightly ahead of the wave trough. Convection sustains the wave circulation through vortex stretching and potential vorticity (PV) generation. The PV dynamics is examined in detail using so-called PV tracers. Figure 29 shows the PV generated by latent heating in a MetUM simulation of an AEW case in July 2010. High-potential vorticity air accumulates around the position of the wave trough indicated by the black line.

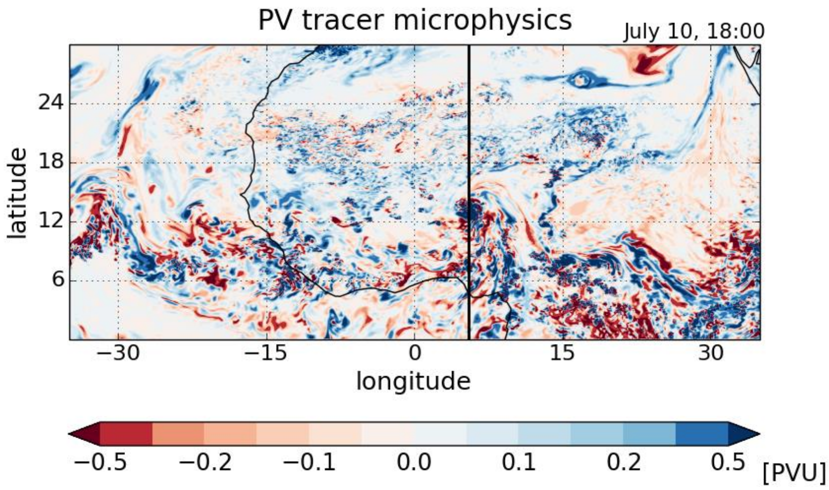


Figure 29: Potential vorticity tracer related to latent heat release in a Met Office Unified Model simulation of an AEW case in July 2010. The vertical black line indicates the wave trough.

Moisture convergence in the lower mid-troposphere ahead of the wave trough plays a crucial role in creating local moist instabilities and triggering and organising convection. Figure 30 summarises key aspects of the convection-circulation interaction in AEWs.

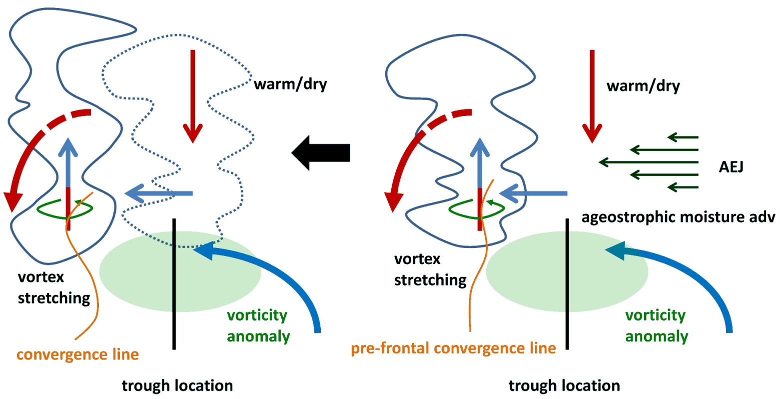


Figure 30: Schematic of the coupling between convection and the atmospheric circulation in African Easterly Waves (from Tomassini et al., QJRMS, 2017).

Next steps

Since the publication of the paper, global 5km convection-permitting simulations of the AEW case described in Tomassini et al. (2017) have been performed and are being analysed. These simulations provide an important link between current and future global model development (see section on WP2), and the CP4-Africa convection-permitting simulations.

Further investigations of the interaction between mesoscale convective systems and the AEW dynamics is being carried out, and a second paper is planned for submission in late spring or early summer 2018 based on the 4.5km global convection-permitting simulations. Figure 31 shows irradiances from the Meteosat Second Generation (MSG) satellite at 10.8 µm for July 13th, 2010, at 18:00 UTC (left panel), and the same quantity simulated based on the 4.5km convection-permitting forecast with 90 hours lead time (right panel). Most of the individual convective systems are reproduced by the model simulation.

Among other aspects, we plan to investigate the process through which high-PV air created by boundary layer mixing over the Sahara is drawn towards the wave trough. As can be seen from Fig. 32, PV is accumulated ahead of the frontal zone of the wave and transported southward by the wave circulation. This mechanism invigorates the wave over the coastal area of West Africa and may be important in the formation of hurricanes over the Atlantic.

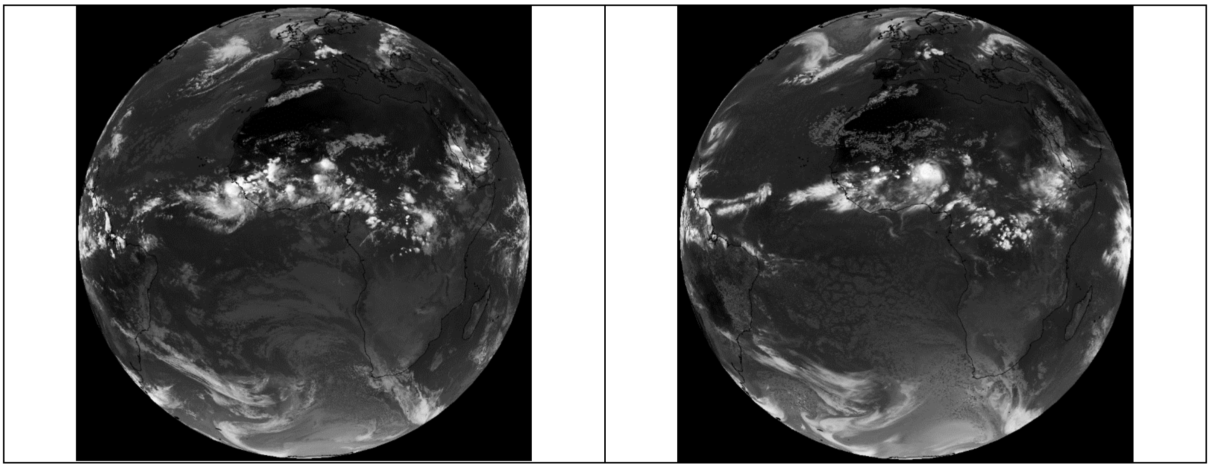


Figure 31: Irradiances at 10.8 µm from the Meteosat Second Generation Satellite on July 13th, 2010, at 18:00 UTC (left panel), and the same quantity simulated based on the 5km convection-permitting forecast with the Unified Model at 90 hours lead time (right panel).

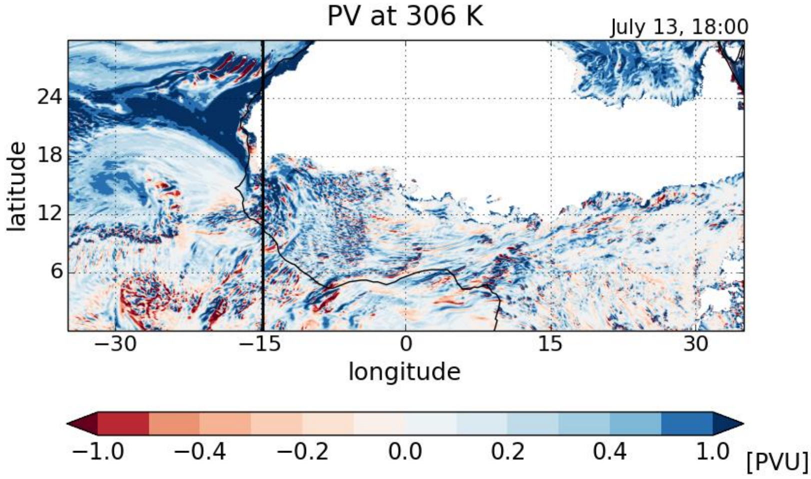


Figure 32: Potential vorticity (PV) on the 306 Kelvin surface on July 13th, 2010, at 18:00 UTC from the 5km convection-permitting UM simulation. Areas where the 306 Kelvin surface hits the ground are in white. PV is accumulated ahead of the wave trough and drawn southward towards the centre of the trough by the wave circulation.

WP4.2 Characterising model improvement in key processes for future climate 5-40 years ahead

Last years' work on a new methodology using a Met Office the Perturbed Physics Ensemble (PPE) to identify the sensitivity of specified climate parameters (e.g. total West African Monsoon rainfall over June-August) to changes in MetUM physics is continuing and is briefly reported under Section 4.1a.

WP4.3 Impact of resolved convection on future projections

Work on the implications of model improvements on assessment of climate change signals is linked with WP2 and has been reported there. Note in particular that CP4-Africa indicates that future increases in extreme 3-hourly (and to a lesser extent daily) precipitation are greater than in the (conventional – i.e. CORDEX type) nCP25-Africa regional model. Also, at the same time, we see a greater tendency for a lengthening of dry spells during the wet season in CP4-Africa.

Next steps:

As the CP4-Africa future (idealised) simulations are completed work on characterising the impact of resolved convection on future projects on the 5-40 year timescale will be consolidated. This work is planned and a number of papers that will be published on specific aspects of the analysis have been identified.

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Appendix 1: Programme for the IMPALA 3rd Science meeting

IMPALA 3rd Science meeting: Progress and plans

12-13 December 2017; *University of Reading*

December 12th

09.00 – 09.05 Welcome/logistics (Andy Turner)

09.05 – 09.15 FCFA update, Cape Town meeting, meeting outcomes, (Cath Senior)

09.15 - 10.45: WP1: The role of the large scale on Africa (*Presentations ~15 minutes including questions, poster introductions – 1 slide)*

Overview of WP1 (deliverables, papers, plans) – Andy Turner (Reading)

WP1.1 – Remote and large-scale drivers of African Climate variability

Michael Vellinga (MO) – African long rains

Linda Hirons (Reading) - What is the role of air-sea coupling and horizontal resolution on the representation of large-scale drivers of African Climate Variability

Mat Collins (Exeter) - cross-equatorial energy transport

WP1.2 – Reducing uncertainty in the final response to remote drivers

Sean Milton (MO) – Nudging experiments (remotely by GoToMeeting)

Martin Willet (MO) - Development of circulation errors in the operational NWP model and the link to climate errors

10.45 - 11.15: Tea/Coffee

11.15 - 12.15: WP2: Improved Representation of local processes (*Presentations ~15 minutes including questions)*

Overview of WP2 (deliverables, papers, plans) – Keith Williams (MO)

WP2.1 – Convective parameterization development

Alison Stirling/Michael Whitall (MO) – Scale Aware convection

WP2.2 – Land Surface Developments

Chris Taylor (CEH) – Land model developments - TBC

Debbie Hemming (MO) – African grassland phenology: sensitivity of JULES modelled LAI to soil and root parameters

12.15 - 13.15: Lunch

13.15 – 14.45: CP4-Africa (*Presentations ~15 minutes including questions)*

Overview of CP4-Africa work – Doug Parker

Rachel Stratton (MO) – Latest results from CP4-Africa control simulations

Sonja Folwell (CEH) – Surface Hydrology in CP4 simulations

Lawrence Jackson (Leeds) - The Annual Cycle of Convection and Rainfall in the Hadley cell over Central Africa

Declan Finney (Leeds, HyCRISTAL) - Effect of explicit convection on simulations of current climate of East Africa

Neil Hart (Oxford, UMFULA) – Tropical Temperate Troughs (TTTs) in CP4-Africa

14.45 – 15:45: WP4: Integration and Characterisation of model improvements and implications for future climate change (*Presentations ~15 minutes including questions)*

Overview of WP4 (deliverables, papers, plans) – Cath Senior (MO)

WP4.1 – Model integration and development

Lorenzo Tomassini (MO) - The interaction between moist diabatic processes and the atmospheric circulation in African Easterly Wave propagation

WP4.3 – Impact of resolved convection on future projections

Lizzie Kendon (MO) – First results from CP4-Africa future experiments

Cathryn Birch (Leeds) – Heatwaves

15:45 - 16.00: Tea/Coffee

16:00 - 17.00: Poster Viewing

Posters:

Segolene Berthou – Improvements in the precipitation distribution of the West African Monsoon with a convection permitting simulation at climate scales.

Dave Rowell/Rob Chadwick – Dominant drivers of Uncertainty in CMIP5 rainfall projections over East Africa

Rachel Stratton- The CP4-Africa control simulation – an initial assessment of the run

Andy Turner – Overview of IMPALA WP1: The impact of large-scaled varianbiltity and teleconnections on African climate variability and change

Linda Hirons – Large scale drivers of variability in the East African short rains

Lorenzo Tomassini – The interaction between moist diabatic processes and the atmospheric circulation in African Easterly Wave propagation

Declan Finney – Pan-African and regional climate in the CP4-a convection-permitting simulations

Sonja Folwell – Surface water balance in a convection permitting model

Chris Taylor – Satellite data show frequency of intense Mesoscale Convective Systems in the Sahel tripled since 1982

Seshu Kolusu – Characteristics of sub-seasonal wet and dry spells over Southern Africa: observations and high resolution models

Neil Hart - The dependence of sub-tropical southern African circulation in the representation of convection in climate simulations

17.00: End of Day 1

18.30: Conference Dinner (self funded) – Bills restaurant

December 13th

09.00 - 10.30: WP3 Metrics and Model Evaluation (*Presentations ~15 minutes including questions)*

Overview of WP3 (deliverables, papers, plans) – Richard Washington (Oxford)

Thompson Annor (U of) - West African Precipitation and Temperature climatology: An Evaluation of the Unified Model on Annual, Seasonal and Monthly time scales

Joseph Mutemi (U of Nairobi) – Evaluation of the UM over East Africa (GoToMeeting)

Wilfried Pokam (U of Yaounde) - Evaluation of UM over Central Africa *(GoToMeeting)*

Babatunde Abiodun (CSAG, U of Cape Town) – Evaluation of the UM over West Africa (GoToMeeting)

Rachel James (Oxford/CSAG U of Cape Town) - Evaluation of HadGEM2-GC2 over southern Africa (GoToMeeting)

10.30 - 11.00: Tea/Coffee

11.00 - 12.00: Plenary discussion/BoGs on cross project deliverables – led by Cath Senior

CP4-A overview paper – including results from across FCFA and potentially first results from impacts studies

CP4-Africa guidance document

12.00 - 13.00: Lunch

1300 - 1530: Infrastructure, cross project issues, FCFA progress (*Presentations ~15 minutes including questions)*

Cross Project and FCFA updates

Richard Graham (MO) – Outcome of annual reporting, Our IMPALA inputs to the FCFA Impact Strategy meeting, Potential FCFA-WISER links

Infrastructure

Cath Senior for Duncan Watson-Parris (Oxford) – Data Management and long term storage questions

(14:00 UTC / 08:00 New Orleans) Tyler Erickson (Google Earth Engine) – The Google Earth Engine Project (GoToMeeting)

Brief Updates on Pillar 1 work in RCs (Presentations ~15 minutes including questions)

Richard Jones (MO) – Update on FRACTAL (Southern Africa)

John Marsham (Leeds) – Update on HyCRISTAL (East Africa)

Chris Taylor (CEH) – Update on AMMA-2050 (West Africa) -TBC

Richard Washington (Oxford) –update on UMFULA (Central/Southern Africa)

15.30 - 16:00: Final discussion and plans for future meetings

16.00: End of Day 2

Appendix 2: Notes on discussion on IMPALA's contribution to cross-FCFA products

IMPALA science meeting 12-13 December 2017

Notes by Richard Graham (15/12/17)

The discussion centred around two products/deliverables highlighted at the mid-term FCFA conference in Cape Town: 1) a BAMS-style paper on CP4-Africa results from across the 5 RCs and covering both present day and future simulations; 2) A set of technical guidance strands for using CP4-Africa results including context of the results and a guide on how to access the data from JASMIN.

1) CP4-Africa BAMS-style paper

The ambition to produce a cross RC paper was strongly supported – though there were differences of opinion on the focus of the paper.

Perspectives offered are briefly summarised below.

CP4-Africa design

- BAMS is a good journal for the paper. The content should include learning on the design of CP4-Africa experiments (which has been considerable – e.g. length of simulations; lateral boundaries; control runs etc) as well as results from the simulations.

Contribution to process understanding

- The paper should bring out the key point that, while convection-permitting simulations are increasingly used, the CP4-Africa simulations are unique in being convection-permitting simulations on climate timescales (present and future) on a large domain over tropical land, which means that, for the first time, mesoscale convective systems (i.e. organised convection) and their life cycle/mechanisms of organisation can be studied over land in detail on longer timescales, both present day and in a future climate. Case studies should be linked to this underlying scientific point.

CP4-Africa user benefit/impact

- Content should be based on end-to-end case studies with a focus on impact and benefits (e.g. city planning, farming) with information that can be used or feed into policy documents. It was noted that care would need to be taken not to "cherry pick" good examples and the challenges associated with CP modelling (e.g. localised excessive rainfall) should also be made clear.
- Impact on the scientific community should also be recorded. For example, AMMA-2050 has well developed plans to use CP4-Africa to drive a hydrology model.
- The point that CP4-Africa has made substantial advances in modelling for a modest financial investment should also be noted (this point also duplicated below)

Promoting the operationalisation of convection permitting high resolution modelling particularly within the CMIP community to feed into the IPCC AR process

- The CP4-Africa experiments are very novel and have only been done for Africa with one model and a single set of experimental parameters. The primary focus of the paper should be on "selling" the idea to promote similar activities at other modelling centres and encourage coordination (e.g. within WCRP, CMIP) on experimental design –

fostering operationalisation and inclusion into the CMIP, IPCC AR process. It was noted that this has not worked fully for the CORDEX simulations.

- The point that CP4-Africa has made substantial advances in modelling for a modest financial investment should also be noted (this point also duplicated above)
- These ideas can be promoted at the planned African Climate Conferences 2019 (the conference is part of the FCFA legacy planning)

2) Technical guidance document(s) for using CP4-Africa outputs

The ambition to generate such documents was strongly supported. There was also support for generating short "glossy" publications on CP4-Africa for the policy oriented audience – and these could include showcase video representations of the simulations. Discussion points included the following:

- The format could use a template similar to that generated for CMIP models by UMFULA (see: *add link*) with drill down to more technical information on how to access and process the data.
- The technical documentation would likely evolve in content and format as lessons are learnt through more researchers accessing the outputs. There is an opportunity to begin collating experiences (both successes and potential pitfalls) as new researchers begin their studies with CP4-Africa – notably the African partners.
- The best format might be a set of on-line strands of information that could be linked in different ways to address specific audiences
- There should be full documentation of the unrealistic aspects of the simulations (include the "good, bad and ugly").

3) Other discussion points

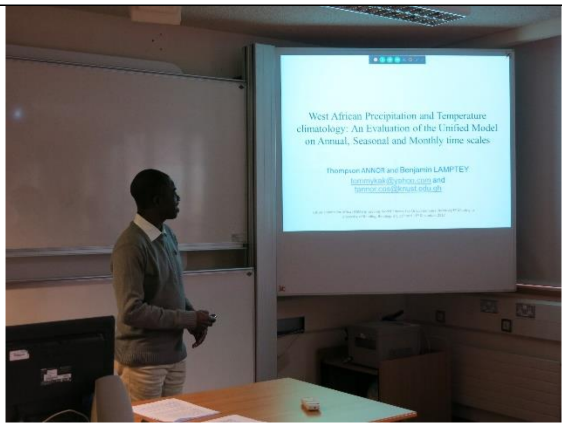
There was a discussion on the longevity of IMPALA data storage on JASMIN, including:

- Need to find out how long data can be stored. It is likely to be used for at least 10 years so very important to have a secure easy accessible data store.
- Other RCs have asked if they can also place data on JASMIN
- JASMIN protocols might be too restrictive to qualify as the public access required at project end and other possibilities need to be considered e.g.
    - IRI Data Library: http://iridl.ldeo.columbia.edu/index.html?Set-Language=en which allows easy download as well as interactive visualisation
    - Google Earth Engine (see presentation from Tyler Erickson)

- Other legacy pathways for IMPALA were also noted particularly the Africa model evaluation metrics hub and associated input to the CMIP ESMvalTool (Rachel James is taking this forward in a separate activity with a concept note already written).
- An opportunity to achieve lasting legacy through links with the DFID-WISER2 Support to ICPAC project was also noted. As part of this risk project Climate Risk Narratives (CRNs) will be developed for East Africa using methods employed in FRACTAL and science from HyCRISTAL. The CRNs could also be informed by CP4-Africa outputs. The CRNs will be integrated into ICPACs operational output as a WMO-designated Regional Climate Centre (RCC). The development of the CRNs will be led by Fred Semazzi (NCSU) – partner in HyCRISTAL.

Photo Gallery

IMPALA PI Cath Senior introduces the 3rd IMPALA Science meeting



IMPALA ECR Thompson Annor (KNUST) presents his MetUM evaluation for West Africa

Break times: viewing posters presented at the FCFA mid-term conference

Rosalind West (DFID) addresses the meeting

Workshop evening meal at Bill’s, Reading