FCFA IMPALA

Report of 2nd IMPALA science meeting

(covering the period Dec. 15 to Jan. 17)

Second IMPALA Science Meeting, University of Leeds, 19-20 January 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 second IMPALA science meeting 19-20 January 2017 and covers work over the year since the first Science Meeting (10-11 December 2015)[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 will facilitate rapid progress which may then be exploited by the wider modelling community – since the methodology developed and understanding obtained will be widely applicable across all contemporary models.

Over the last year all project governance mechanisms have remained active and good progress has been made across IMPALA's four work packages. In brief, research has contributed to improved rainfall simulation over Africa in the latest release of the MetUM and significant additional improvements have been developed that will be pulled-through into the model in years 3 and 4 of the project. A large body of research is gaining momentum and is clarifying the role of remote and local drivers on African climate and sources of model error in these drivers - providing key information to steer further model improvements (with 3 published papers this year). Simulations with the pioneering high resolution, convection permitting CP4-Africa model are underway and outputs are being analysed by IMPALA and the Regional Consortia (RCs). Initial results show very substantial improvements to many aspects of rainfall representation: reduced seasonal biases in totals and number of rain days, improved cell propagation, improved diurnal cycle and improved rain intensity spectrum. With collaboration from African partners a model evaluation framework for Africa has been developed, the baseline MetUM has been evaluated over regional and pan-African domains, and a paper describing both has been accepted for publication.

Management and project meetings

The IMPALA project management committee (comprising the WP leaders) met on 9 December 2016 and the first meeting of the IMPALA Scientific Steering Group is being scheduled for September 2017 in conjunction with the mid-term FCFA conference in Cape Town.

IMPALA has engaged with CCKE on a number of activities including: preparation of the first (2016) DFID annual review of FCFA; revision of the FCFA logframe (completed February 2017); meeting with the CCKE team during their "deep dives" with UK-based FCFA partners in October 2016; preparation of IMPALA applications to the Innovation and Mobility Funds; and contributions to the FCFA website. Additionally, an IMPALA contribution on "The need for improved model capability for African climate" was prepared and published in the FCFA publication "Africa's Climate"[2] which was launched at COP22. Also at COP22 IMPALA (and other FCFA) results were shared during a Met Office and SouthSouthNorth joint Side Event: "From science to services: Improving climate resilience in Africa".

A successful 2-day WP3 model evaluation workshop was held at Oxford University (16-17 March 2016), and was instrumental in preparation of the paper on model evaluation now

[1] http://www.futureclimateafrica.org/wp-content/uploads/2017/05/impala_science_meeting_dec15.pdf

[2] http://www.futureclimateafrica.org/wp-content/uploads/2016/11/africas-climate-final-report-4nov16.pdf

accepted for publication in the Bulletin of the American Meteorological Society (BAMS) entitled: "Evaluating climate models with an African lens". The model evaluation workshop was followed by a 1-day Africa Process Evaluation Group (PEG) meeting (18 March 2016) which include presentations from the IMPALA Africa-based partners. Two further Africa PEG meetings were held on 12 October 2016 and 27 April 2017. The cross-FCFA Working Group on the CP4-Africa model has met 4 times since December 2015 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 Leeds, 19-20 January 2017 and is the subject of this report. The meeting was attended by around 40 scientists engaged in the project and included representatives from all 4 Regional Consortia and the 4 IMPALA African partners (by video link). The meeting included discussion sessions to consider additional experiments for the CP4-Africa model and to clarify linkages and joint activities between WP1 (remote influences) and WP2 (local processes).

Papers (submitted/published), internal project reports
Three peer-reviewed papers have been published this period with a further three papers accepted/submitted for publication and several more in preparation. Specifically:

Hawcroft et al. 2016: Southern Ocean albedo, inter-hemispheric energy transports and the ITCZ: global impacts of improving top of atmosphere radiation biases in a coupled model
Hawcroft et al. 2017: The contrasting climate response to tropical and extratropical energy perturbations (*in review*)
James et al. 2017: Evaluating climate models with an African lens. *(in review)*
Johnson et al. 2016: Evaluation of biomass burning aerosols in the HadGEM3 climate model with observations from SAMBBA,
Stephens et al. 2016: The curious nature of the hemispheric symmetry of the Earth's water and energy balances.
Tomassini et al. 2017: The interaction between moist diabatic processes and the atmospheric circulation in African Easterly Wave propagation (*submitted*)

Progress highlights
Progress highlights are summarised below by work package.

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

- The quasi circum-tropical rain band known as the Intertropical Convergence Zone (ITCZ) is located too far south on average in the MetUM and many other climate models. Last year it was demonstrated that simple, idealised corrections to hemispheric albedo (the MetUM is too dark in the southern hemisphere) bring remarkable improvements to ITCZ positioning and associated lessening of the Sahel dry bias. The challenge is to replicate these results through physically justified changes to model physics. To advance this aim, this year new results have begun to clarify the relationship between cross-equatorial energy transport and ITCZ positioning under albedo changes of different magnitude and applied at different latitudes. Three peer-reviewed papers have now been published on this research.
- Following foundational work last year which characterised the MetUM's performance across a range of key remote climate drivers for Africa: ENSO, the Indian Ocean Dipole (IOD), the Equatorial Atlantic, the Mascarene High (MH), Quasi-Biennial Oscillation (QBO) and the Madden-Julian Oscillation (MJO), further process-based diagnostic analyses have continued to advance understanding of the mechanisms that underlie model errors. For example, spatial errors in the way moisture transport into East Africa responds to IOD and MH forcing have been uncovered and it has been found that the MetUM is symmetric in its response to anomalous zonal positioning of the MH ridge –

whereas in observations only eastward displacements are associated with a rainfall response (enhanced in this case). These findings are a key step towards identifying and correcting the source of the model errors.

- New diagnostic tools have been developed and employed to diagnose a) the impact of model biases remote from Africa on errors over the continent and b) the impact of errors in local processes over Africa in feedback to the large-scale circulation. In a specific application of the first tool, model precipitation errors over the Indian Subcontinent during the monsoon season, related to heating and circulation errors have been shown to generate errors in the upper wind field over Africa – which in turn are related to precipitation errors over West, Central and East Africa. This work is identifying remote sources of model error over Africa and informing the targeting and priorities of IMPALA model development.
- In specific work to identify drivers of the East Africa March-May (MAM) season the MJO, Sea Surface Temperature (SST) anomalies in the northern Indian Ocean and diabatic heating anomalies over the Maritime Continent have been found to explain about two thirds of the MAM interannual variability. The MetUM's representation of these drivers is now being analysed in depth.

WP2: Improved representation of local processes

- A major weakness in climate models – representation of tropical convection – continues to be addressed with additional significant advances this year. Improvements have taken place on several fronts: notably, better convective storm clustering/organisation reported last year (through the prognostic convective entrainment) has now been further enhanced by new treatments of convective inhibition (CIN - a stability related parameter) and further improvements are being explored through implementation of cold pool parameterisation to introduce more realistic convective triggering. In addition, underpinning research is underway to further inform improvements in convection parameterisation and is using idealised simulations at very high resolution (up to 100m).
- The design and testing of the convection permitting high resolution runs was completed last year and this year both present-day and idealised future runs are in production. The present-day simulations have completed 4 years and output is being analysed within IMPALA and by Regional Consortia. The CP4-Africa simulation has reduced rainfall biases over land relative to control run. Notably a near removal of the persistent dry bias over the Sahel and Guinea Coast is achieved. CP4-Africa improves the propagation of convective systems both over East Africa and over West Africa in association with African Easterly Waves. The intensity spectrum of short-lived rain events is also improved as is the diurnal cycle in rainfall. These results are very encouraging evidence of an improved modelling physical basis – enabling generation of credible information on the importance of modelling "weather processes" in climate change projections.
- Last year work on land surface processes focussed on developing improvements to land surface representation for use in the CP4-Africa simulations. This year work has been directed on improving a number of aspects of the Joint UK Land Environment Simulator (JULES) – the MetUM's land surface model - important for predicting climate change, specifically: canopy interception loss, root zone soil moisture, drought deciduous phenology and photosynthesis. It is found that the MetUM produces unrealistically high annual values of interception loss because rainfall is generally too light and is consequently trapped in the canopy and re-evaporates before entering the soil. Canopy interception losses in the CP4-Africa simulations – with improved rainfall intensity spectrum – are currently being studied.
- This year testing of a satellite-based preferential source mask, to improve the MetUM's spatial distribution of dust emissions, has been completed. The new scheme improves the distribution of dust, though further work is required to recalibrate the total emission amounts. In addition, improvements have been made to the representation of biomass burning aerosol by incorporation of the new Global Model for Aerosol Processes

(GLOMAP-mode) modal aerosol scheme in the HadGEM3 climate model. Improvements were demonstrated by comparing HadGEM3 simulations with field campaign measurements including over West and southern Africa.

WP3: Metrics and Model Evaluation

- Refinement of process-based metrics pertinent to model evaluation on pan-African and regional scales (East, West, Central and southern Africa), and application of the metrics in a performance analysis of the baseline MetUM (GA6/GC2) has continued in close collaboration with the 4 IMPALA African partners who have analysed model simulations for their regions.
- A 2-day model evaluation workshop (16-17 March 2016) was held at the University of Oxford and attended by Africa partners. The workshop successfully synthesised evaluation results and agreed the scope and content of a peer-reviewed publication.
- Building on the above activities a position paper has been prepared, in co-authorship with African partners, and has been accepted for publication in the Bulletin of the American Meteorological Society. The paper, "Evaluating climate models with an African lens" (James et al.) recommends example process-based evaluation metrics for each region, applies the metrics in an evaluation of the baseline MetUM and encourages collaboration between model developers and African scientists to deliver a coordinated hub of model metrics for Africa to promote accelerated progress in model development for the continent. The paper received very positive reviews.

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

- A comprehensive assessment over Africa of the GA7/GC3 MetUM version, the successor to the IMPALA baseline version (GA6/GC2) has been achieved. Results have been documented and are available to RC Pillar 1 researchers on the Met Office collaboration twiki pages. A key result is that the dry bias in MetUM West African Monsoon (WAM) precipitation a very common and long-standing error in climate models, is reduced at GA7 relative to GA6, though substantial biases remain in the global simulations.
- African Easterly Waves (AEWs) are a key generator of rainfall in the WAM and to aid targeting of work on further model error reduction – a detailed study of the structure of observed and simulated AEWs has been conducted. Important differences are found in the alignment of the main rainfall regions with the wave axis that may be key to obtaining the improved simulations of the wave propagation.
- A tool to diagnose the impact of model changes on results from future climate projections is being developed. The tool is based on a large perturbed physics ensemble (518 simulations) of the GA7/GC3 MetUM. In preliminary tests of the tool on present-day climate simulations June-August rainfall totals over West Africa are found to be most sensitive to changes in the convective entrainment rate, as might be expected, but also to cloud radiative effects and cloud lifetime. The method provides insight to aid further targeted research to improve understanding of these sensitivities – leading to sustainable model improvements.

Update on delays to CP-4 Africa idealised experiments

As a result of slower than anticipated processing on the HPC system (a development that is beyond IMPALA's control) delivery of the full 10 years of CP4-Africa present-day and idealised future simulations is now expected in mid-2018, later than first expected. Two parallel runs of 5 years each for both present day and future simulations are being run consecutively to limit the delays. Early access to and analysis of the simulations that are already available (such as is already underway by AMMA-2050 and HyCRISTAL) will be promoted including through activities at the September 2017 FCFA conference.

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 second IMPALA science meeting 19-20 January 2017 and covers work over the year since the first Science Meeting (10-11 December 2015).

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 will facilitate rapid progress which may then be exploited by the wider modelling community – since the methodology developed and understanding obtained will be widely applicable across all contemporary 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 release 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 will also characterise 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 will include 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 (comprising the WP leaders) met on 9 December 2016 to review project functioning, plan project events – notably the 2nd IMPALA Science meeting at University of Leeds - and to review and provide internal steering to science. Good progress against deliverables has been made across all work packages. The first meeting of the IMPALA Scientific Steering Group is being scheduled for September 2017 in conjunction with the mid-term FCFA conference in Cape Town.

IMPALA has engaged with CCKE on a number of activities including: preparation of the first (2016) DFID annual review of FCFA; revision of the FCFA logframe (completed February 2017); meeting with the CCKE team during their "deep dives" with UK-based FCFA partners in October 2016; preparation of IMPALA applications to the Innovation and Mobility Funds; and contributions to the FCFA website. Additionally, an IMPALA contribution on "The need for improved model capability for African climate" was prepared and published in the FCFA publication "Africa's Climate"[3] which was launched at COP22 (see below).

IMPALA (and other FCFA) results were shared during a Met Office and SouthSouthNorth joint Side Event at COP22: "From science to services: Improving climate resilience in Africa". The side event was based around a panel discussion on the following themes: what are the "burning questions" that are shaping frontier climate research and climate information services (CIS) for Africa?; How can research agendas be aligned to support implementation of the Paris Agreement (notably Article 7)?; How are scientific advances being translated into improved CIS to support development objectives?; What are the key challenges to progressing this work?; What are the key opportunities for partnerships and learning? A blog of the event is available[4].

A 2-day WP3 model evaluation workshop was held at Oxford University (16-17 March 2016). The workshop included participation from Africa-based IMPALA partners Joseph Mutemi (IGAD Climate Prediction and Applications Centre (ICPAC)/University of Nairobi), Wilfried Pokam (University of Yaoundé) and Babatunde Abiodun (University of Cape Town). The workshop reviewed evaluations of the "baseline" MetUM and scoped the structure and content of a paper on model evaluation now accepted for publication in the Bulletin of the American Meteorological Society (BAMS) entitled: "Evaluating climate models with an African lens".

The model evaluation workshop was followed by a 1-day Africa PEG meeting (18 March 2016) which include presentations from the IMPALA Africa-based partners. Two further Africa PEG meetings were held on 12 October 2016 and 27 April 2017. Discussions of IMPALA results have featured prominently in these meetings.

The cross FCFA Working Group on the CP4-Africa model has met 4 times since December 2015 and has completed its work on the design of the simulations, for both present-day and idealised future periods. The WG remains active to monitor output, discuss technical issues arising during the runs, facilitate dissemination to the RCs and to plan the science and papers arising from the analysis.

[3] http://www.futureclimateafrica.org/wp-content/uploads/2016/11/africas-climate-final-report-4nov16.pdf
[4] http://www.futureclimateafrica.org/news/cop22-delegates-hear-how-african-climate-information-is-getting-better-and-more-widely-used/

An IMPALA science meeting was held at the University of Leeds, 19-20 January 2017 and is the subject of this report. The meeting was attended by around 40 scientists engaged in the project and included representatives from all 4 Regional Consortia. The programme is included in Appendix 1. IMPALA scientists, including the four scientists from African institutions (by Skype link), presented their progress and plans on all work packages. 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 possible additional CP4-Africa experiments and on interactions between WP1 (large scale drivers) and WP2 (local processes) – a summary of the discussions is in Appendix 2.

3. The MetUM development approach

For reference later in this report we here 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 latest model version (GA7/GC3) has been available in test form for analysis this period, but release of a consolidated version was delayed to January 2017. Evaluation results reported her mainly concern GA6/GC2 ("baseline") and GA7/GC3. The next atmospheric version release (GA8) is expected in spring 2018 and GA9 in spring 2019 (Table 1).

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	Expected spring 2018	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 1: HadGEM3 model versions tested and to be tested in IMPALA

Evaluation experiments include 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.

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 are developing 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 through a web-interface. This lowers the barriers to entry for project partners who may not have the infrastructure available to perform these tasks locally. On-going support is provided for the shared group workspace - a large project data store for individual and collaborative working, as well as a mechanism for sharing selected data more widely.

4. Progress

In this section progress to January 2017 is presented for all 4 work packages.

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

Last year's results 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 onset in the Sahel. Experiments with more realistic corrections to albedo were found to not reproduce these improvements. Further experimentation was underway to better understand the mechanisms involved and to exploit understanding in model improvement.

A further finding was 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 highlighted 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.

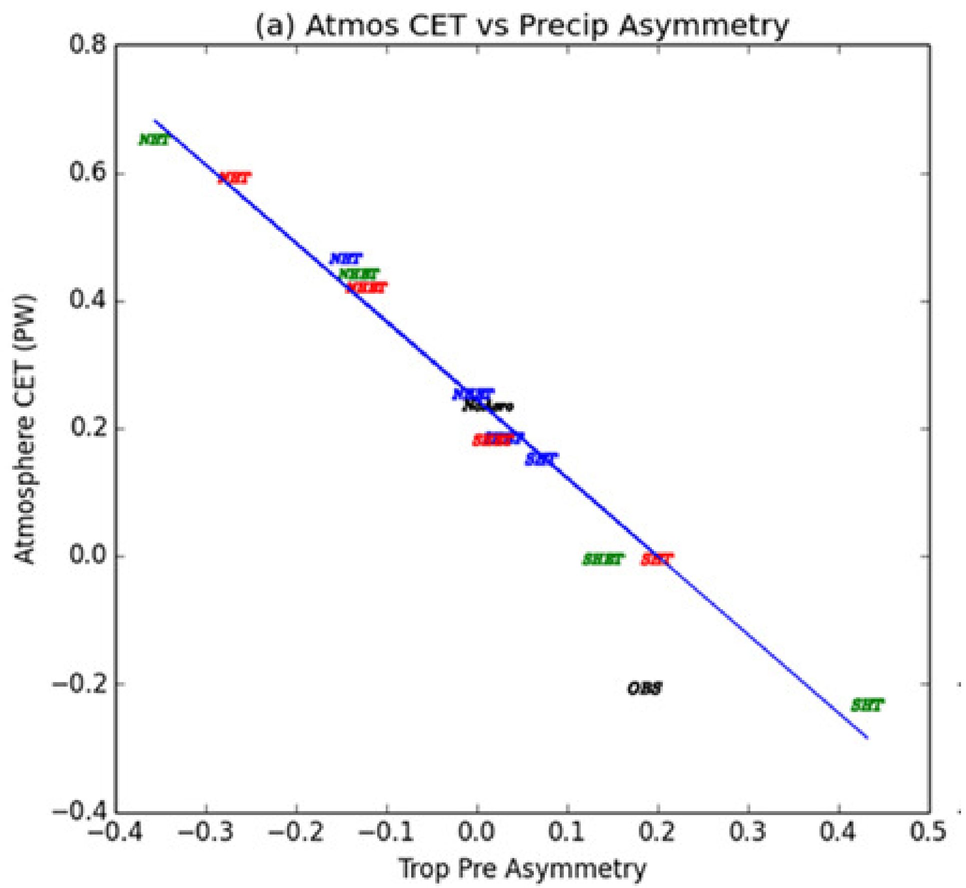
The experiments with more realistic corrections to albedo conducted last year suggested that the cross-equatorial energy transport was sensitive to the latitude at which the albedo was adjusted. This year, new experiments conducted have increased understanding of this sensitivity as well as the relationship to cross-equatorial asymmetry in rainfall. Asymmetry in rainfall is associated with latitudinal ITCZ positioning. In the MetUM the ITCZ is typically located too far south - resulting for example in a dry bias over the Sahel. The relationship between cross-equatorial energy transport and asymmetry in tropical Sea Surface Temperatures (SST) has also been analysed. Three peer reviewed papers have now been published describing results on this research focus (WP1.1a): Hawcroft et al. 2016, Haywood et al. 2016 and Stephens et al. 2016.

The new experiments (to be published as Hawcroft et al., 2017) were conducted with HadGEM2-ES. Results confirm a strong sensitivity of tropical precipitation/ITCZ positioning to the latitudinal distribution of perturbations to the energy budget and further highlight the robust relationship between cross-equatorial atmospheric energy transport, tropical precipitation and SSTs. In the experiments, changes in albedo are generated by inserting aerosol in the stratosphere, increasing reflectance and decreasing the incoming short wave radiation and atmospheric heating. In separate experiments, idealised loadings of aerosol were inserted into one of four latitudinal bands: northern hemisphere (NH) tropics (NHT), NH extratropics (NHET), southern hemisphere (SH) tropics (SHT) and SH extratropics (SHET). For each latitudinal band experiments with different aerosol amounts (Aerosol Optical Depth, AOD) were run: specifically, 1AOD, 2AOD and 4AOD - where amounts in 2AOD were roughly equivalent to releases during the Mount Pinatubo eruption (more aerosol means higher albedo). In this way, the tropical response to changes in the energy budget in each hemisphere and in differing latitudes was examined.

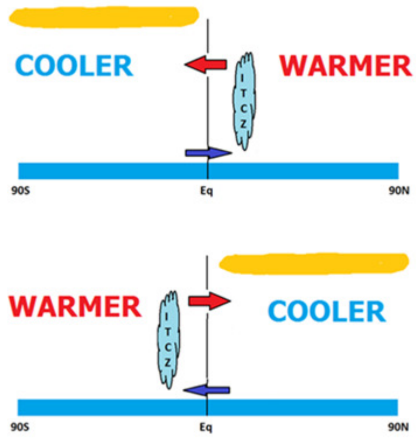
The differential dynamical responses were found to be complex, but the strong relationship between cross-equatorial energy transport in the atmosphere (CETA) and asymmetry in precipitation across the equator (as measured by a precipitation asymmetry index, PAI) is remarkable given the idealised and large forcings applied to the model (Fig. 1a). In general, the largest responses were seen for increased albedo in the tropical bands and in the 4AOD experiments with increased albedo in the southern/northern hemisphere associated with increased/decreased north-to-south atmospheric energy transport and more northerly/southerly positioning of the ITCZ (positive/negative PAI). The relationship is evident in Fig. 1a and illustrated schematically in Fig. 1b.

Large perturbations (4AOD) applied in the SHT band were the only combination that forces a model cross-equatorial energy transport, and partitioning between ocean and atmosphere, that is similar to the observed (CERES) transport. In particular, the model's erroneous south-to-north directed transport (See 2016 report Fig. 1a) is reversed to north-to-south in this experiment, consistent with the observed transport. A similarly strong association to that between CETA and PAI (Fig. 1a) was also found between CETA and asymmetry in tropical SST (not shown).

The work described is also feeding into new evaluation metrics which are to be used in the Hadley Centre as part of their model evaluation and development process.



a)



b)

Figure 1: **a)** The relationship between cross-equatorial energy transport in the atmosphere (CETA – south-to-north transport is defined as positive) and tropical precipitation asymmetry (PAI, being a measure of the normalised ratio of precipitation from 0˚N-20˚N to 20˚S-0˚S, positive/negative PAI means more rainfall north/south of the equator) in coupled simulations of HadGEM2-ES where the top of atmosphere energy budget has been perturbed (albedo increased) in the southern and northern tropics (SHT, NHT) and southern and northern extratropics (SHET, NHET) via injection of stratospheric aerosol concentrations – results with weakest to strongest perturbations (1AOB, 2AOB, 4AOB – see text) shown in blue, red and green respectively. NoAero is a control simulation with no perturbation and OBS shows the observed relationship. **b)** schematic summarising the impact of the perturbations (yellow represents inserted aerosol) and ITCZ positioning response.

Next steps:
Experiments are underway to contribute to a model intercomparison project (MIP) which is being co-led from Exeter. This MIP will evaluate the response across several state-of-the-art coupled models to idealised energy budget perturbations with a view to distinguishing the processes which govern their responses and the spread of response across the ensemble. This MIP approach is supplemented by evaluation of similar metrics in a perturbed parameter ensemble of the latest Hadley Centre model. Through these two routes, it is 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[5] and the (associated) representation of monsoon precipitation.

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

Last year, the MetUM's representation of the influences of ENSO, IOD, the Equatorial Atlantic, the Mascarene High, QBO and MJO on African climate was characterised and the role played by model resolution and ocean-atmosphere coupling in representing the local response component of teleconnections was investigated. Diagnostic techniques to measure 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).

This year further analysis has focussed on the Greater Horn of Africa (GHA) region both for the Short Rains (October to December) season and the Long Rains (March to May) season. In addition, first results are now emerging from two techniques that have been developed to diagnose a) the impact of remote influences on Africa, in particular how model biases in remote regions can negatively impact on performance for Africa; and b) the way local processes (e.g. convection) over Africa interact with the large-scale flow.

a) GHA Short Rains (SR) season

Last year the model representation of observed teleconnections of GHA rainfall with ENSO, the Indian Ocean Dipole (IOD) index and zonal displacements in the Mascarene High (MH) were characterized for the baseline MetUM in both atmosphere-only (GA6) and coupled (GC2) configurations and at two resolutions N96 and N216 (Table 2). It was found that these teleconnections are well captured in GC2-N216, although there are some spatial differences in the teleconnection patterns. For example, for the teleconnection to ENSO, observed SR rainfall responds most strongly to SST in the eastern tropical Pacific, whereas GC2-N216 rainfall responds most strongly to central Pacific SST.

Work this year shows further that, when forced with observed SST, the strength and spatial pattern of the tropical Pacific teleconnection is more realistic (and is best with GA6-N96), suggesting coupled processes are involved in the GC2-N216 differences from observation. With regard to the IOD, GC2-N216 was found to show a spatial distortion of the SST pattern relative to observations – with the pole in the southeastern Indian Ocean erroneously elongated westward along the equator. It was also found that the GC2-N216 reproduces similar-to-observed IOD-like SST anomalies in association with an eastward extended MH, though the amplitude of the modelled anomalies is too weak. The anomalous easterly flow was also found to be too weak, suggesting a possible lack of moisture advection towards the GHA.

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

Model	Coupling	Atmos. Resolution	Length of simulation
GC2-N96	Yes, GA6 coupled to ORCA025	N96 ~ 135km	100 years
GA6-N96	No, GA6 atmosphere only forced by observed SSTs	N96 ~ 135km	27 years
GC2-N216	Yes, GA6 coupled to ORCA025	N216 ~ 60km	100 years
GA6-N216	No, GA6 atmosphere only forced by observed SSTs	N216 ~ 60km	27 years

Table 2: MetUM configurations used in processed-based analysis of drivers of the Greater Horn of Africa Short Rains and other regions/seasons.

The model's representations of IOD, MH and the GHA SR have been further examined and the moisture flux response to different phases of the IOD and MH zonal displacements has been investigated. The importance of resolution and ocean-atmosphere coupling in the model response has been explored through use of the 4 model experiments in Table 2: GC2-N96, GA6-N96, GC2-N216 and GA6-N216.

The connections between IOD, MH and GHA SR rainfall are summarized in Fig. 2 and Table 3 across all 4 model configurations and observations. It may be seen (Table 3) that model correlations of MH eastern ridge (MHER) zonal displacement and IOD index are marginally closer to the observed value (0.52) in the coupled integrations. While this may not be statistically significant given the relatively small number of years for GA6 (27), inspection of composites of SST stratified by MHER zonal displacement support better performance by the coupled configurations - which capture an SST response much closer to the observed response. All models exhibit a positive correlation between rainfall and IOD (Table 3). The correlation is closest to the observed value in GA6-N96. The correlation is too weak in both the coupled simulations but higher resolution brings a substantial benefit – with the GC2-N216 correlation more closely matching the observed. The positive correlation between MH eastward displacement and GHA rainfall is present in all models except GA6-N216

It is interesting to note that, in observations, while increasing eastward displacements of the MHER (mean observed position ~90˚E) are associated with increasing positive IOD and wet anomalies (Fig. 2a), westward displacements are not clearly associated with negative IOD or dry anomalies (note the "elbow" in the scatter near 90˚E). There is some evidence of this behavior in the GA6 simulations (Figs. 2d&e). In contrast, in GC2, westward displacements of the MH are associated with more negative IOD and dry anomalies (there is no obvious "elbow" in the scatter). This suggests that mechanisms that drive the asymmetry (at present unknown) are not well represented in the coupled configurations.

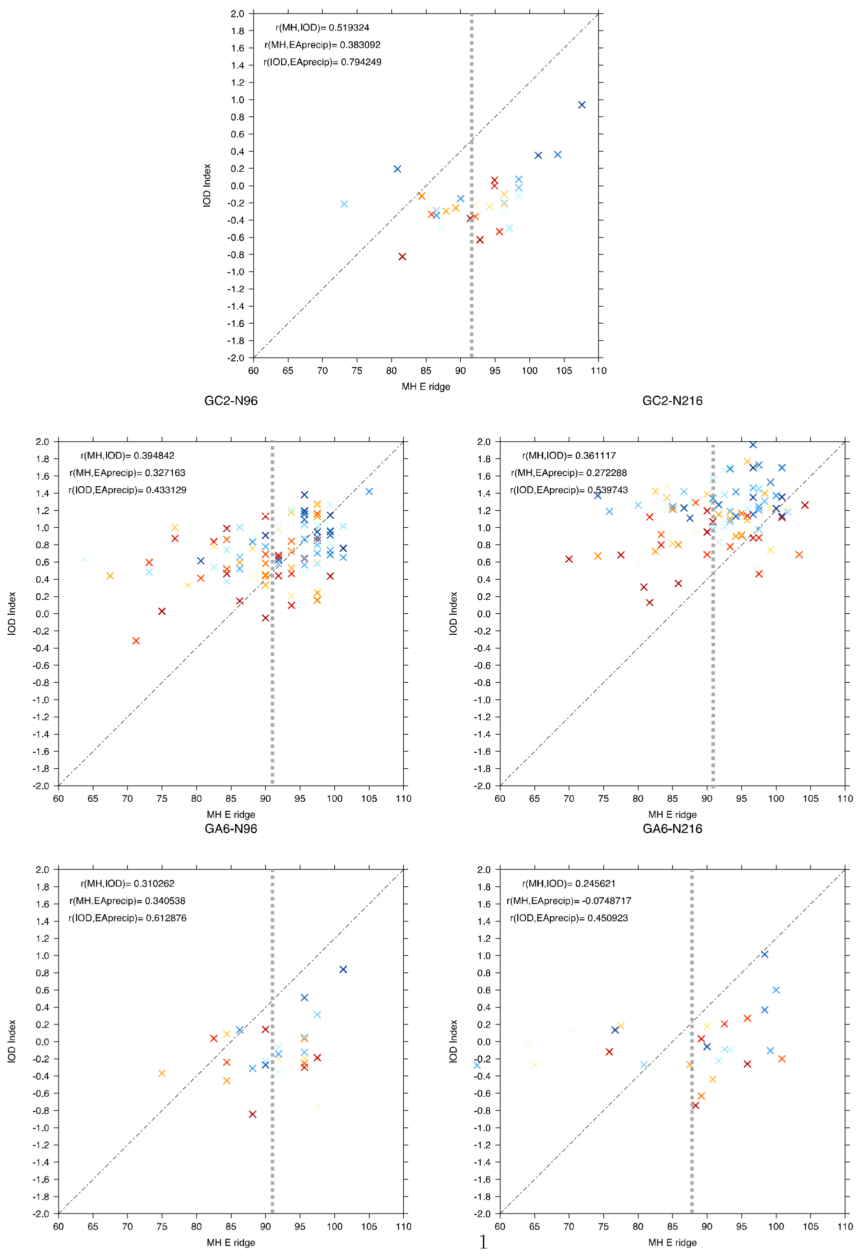


Figure 2: Indian Ocean Dipole (IOD) Index versus longitude of eastern ridge of the Mascarene High (MH), coloured by GHA October-December rainfall anomaly: light blue to dark blue = increasing wet; orange to red = increasing dry. For (a) 36 years of observations (ERA-Interim (MH), HadISST (IOD) and GPCP rainfall); 100 years of GC2-N96 (b) and GC2-N216 (c); and 27 years of GA6-N96 (d) and GC2-N216 (e). The vertical dashed lines show the mean position of the MH eastern ridge (in observations and each model as appropriate). Note, the IOD index shown here is not normalised, it is calculated as the area-averaged SST in the western IO minus the area-averaged SST in the eastern IO (both absolute values). This is done to expose biases in the model's SST distribution.

	Obs	GC2-N96	GC2-N216	GA6-N96	GA6-N216
MH vs IOD	0.52	0.39	0.36	0.31	0.25
MH vs GHA ppn	0.38	0.33	0.27	0.34	-0.07
IOD vs GHA ppn	0.79	0.43	0.54	0.61	0.45

Table 3: Correlations between MH zonal displacement, IOD and GHA SR rainfall in observations and MetUM integrations

Anomalous easterly flow in the tropical Indian Ocean associated with easterly displacements of the MHER and positive IOD is found to be too weak in the MetUM and this may cause errors in the moisture flux into the GHA region. This has been investigated further by compositing the 20% most positive IOD seasons and the 20% most easterly MH displacements. Moisture transport appears similar in both composites, as expected from the aforementioned linkage between IOD and MH. Easterly moisture transport is weaker and covers a narrower equatorial swathe in the MetUM, particularly in GC2.

A striking feature of the observed moisture transport is that it bifurcates near 56˚E, with peak westward transport continuing north and south of the equator. To further investigate the role of the IOD and MH in this double structure the zonal moisture flux at 56˚E (which is the eastern boundary of the CP4-Africa model) was regressed against the IOD index and MHER position (Fig. 3). In observations, easterly displacements of MHER and positive IOD are associated with increased westward moisture flux peaking north and south of the equator with the southern peak more prominently driven by the MH. This structure is almost completely absent from GC2 – with both resolutions showing a single peak near the equator. In contrast the GA6 integrations do show a degree of double structure but the amplitude and separation is too small at both resolutions.

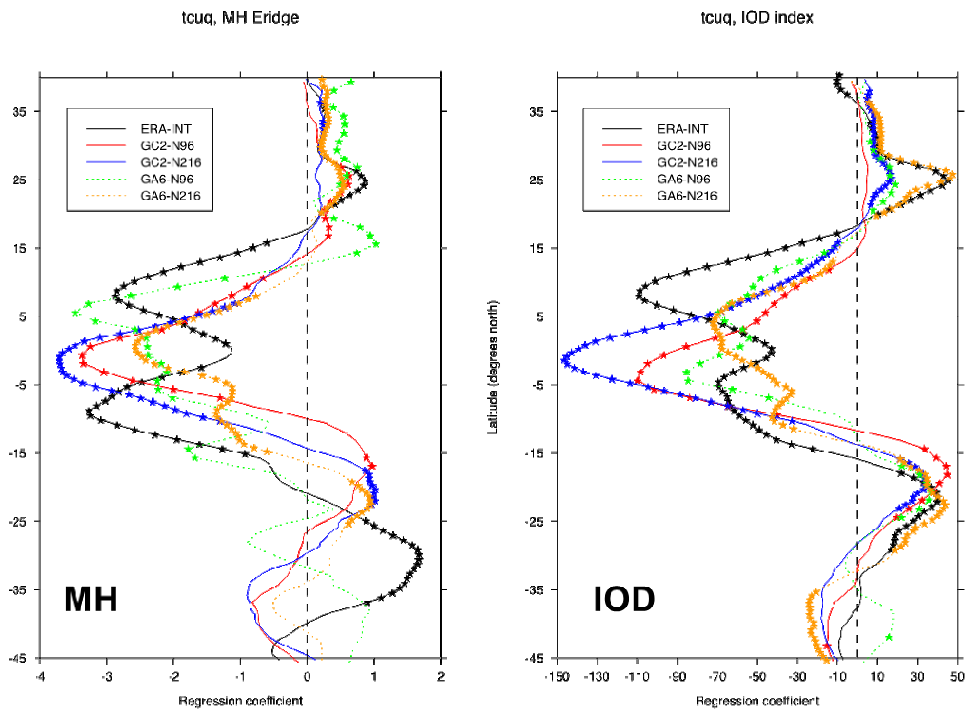


Figure 3: Zonal moisture flux at 56˚E regressed against MH eastern ridge position (left) and IOD index (right) at a range of latitudes centred on the equator. Stars indicate where the regression coefficient is significant at the 5% level. 56˚E is the eastern boundary of the CP4-Africa model.

Next steps:
The analysis will be extended to the new MetUM GC3 and GA7 simulations to monitor the impact of model development on representation of GHA rainfall and moisture transport responses to IOD and MH. The GA6/GC2 failure to replicate the pattern of moisture fluxes (e.g. double structure) across the Indian Ocean in response to the IOD and MH (and thus its impact on East Africa) will be compared with other CMIP5 models. This work will demonstrate the impact of ocean SST errors and remote impacts of diabatic heating on the teleconnection responses. A paper will be prepared in contribution to deliverable D1.1b.

b) MAM Long Rains (LR) season

Results from last year confirmed that the MJO and QBO have moderately strong links to the LR, strongly exceeding the (near absent) constraints by tropical SST.

Work this year has identified two further drivers of LR variability in addition to the MJO and QBO: diabatic heating anomalies over the Maritime Continent (MC) and SST variability in the northern Indian Ocean. Work has concentrated on clarifying the role of the identified remote drivers for year-to-year LR variability. In addition, 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.

Early studies found that the observed relationship between QBO and LR variability is absent from the model and so further model-based studies to understand this driver are not possible. The QBO itself is highly predictable – and thus the failure of the MetUM to capture its influence on convection represents an important loss of potential LR predictability which needs attention. We have focused on understanding the three other teleconnections that we identified in reanalyses: (1) the Madden-Julian Oscillation (MJO) (2) diabatic heating anomalies over the Maritime Continent and Western Pacific. (3) SST in the northern Indian Ocean. Individually these teleconnections are moderately strong but together explain up to two-thirds of the March-April mean rainfall variance in reanalyses. These three teleconnections are also seen in the instrumental record (Fig. 4 for the MJO) but can be masked by observational uncertainty in precipitation estimates due to poor sampling in the gauge network or biases in satellite estimates. Work is ongoing to further understand the dynamics of these teleconnections.

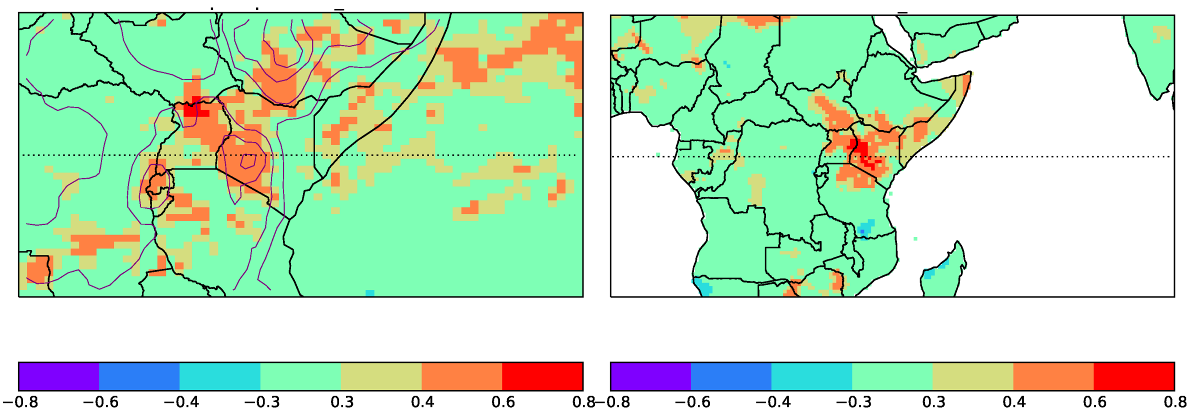


Figure 4: Correlation between March-April mean rainfall and MJO amplitude (all phases) in February-March. Left is for MERRA2 reanalyses (1980-2016), right is for UDEL_vn4.01 monthly gauge data and Bureau of Meteorology MJO index (using satellite OLR and NCEP2 zonal winds, 1979-2014)

We have investigated the presence of the three teleconnections in the latest GA7/GC3 UM configurations and in GA6 experiments where the model is nudged to ERA-I reanalyses. Preliminary indications are that the northern Indian Ocean SST teleconnection (3) is seen in the higher resolution coupled model (GC3-N216) and that the MJO teleconnection (1) is not seen in any configuration, but is present in GC2 hindcasts with GloSea5 initialized around 1 February. There is some evidence that the Maritime Continent diabatic heating teleconnection (2) is present in GA7 but not in either resolution of the coupled (GC3) MetUM.

Next steps:
A paper on the remote drivers of LR variability will be prepared as a contribution to deliverable D1.1b. The MetUM's representation of the drivers will be analysed in more depth, including through nudging experiments (see next section), to elucidate role of model biases on the realism of the representation. New, idealised CP4-Africa and nCP25-Africa case studies will be considered - to examine the local LR response to QBO, MJO.

c) Diagnosing remote and locally forced systematic errors over Africa
We have developed two complementary diagnostic techniques within the framework of the MetUM to aid understanding of the impact of remote influences on Africa, and the interplay between remote and local processes. The first is the nudging technique (Klinker (1990)) in which MetUM simulations, as they evolve, can be nudged back to "truth" (i.e. the ERA-I re-analysis fields) over a specific domain. The technique allows an assessment of the role of biases originating from that domain on the model's climate over Africa. As an example, we have nudged the winds and temperatures over the South Asian Monsoon (SAM) region, during the June-August (JJA) season to ERA-I observations (Fig. 5). This SAM domain was chosen as it exhibits large biases in precipitation (Fig. 5b), diabatic heating and circulation during the South Asian summer monsoon which are candidates for transferring remote errors to Africa and impacting on the JJA seasons in West and East Africa. The N96 AMIP CONTROL simulation of the MetUM (Fig. 5c) has large zonally oriented errors in the 200hPa winds over the tropical Indian Ocean, equatorial Africa, and over South Africa and into the Southern Ocean.

Nudging the simulation back to ERA-I over the SAM domain has a huge impact over Africa, reducing the 200hPa windspeed biases substantially (Fig. 5d). The difference plot, CONTROL-SAM Nudging (Fig. 5e), shows the component of the error that is forced from the SAM region. This is a significant fraction of the total error (CONTROL - ERA-I, Fig. 5c). These upper level (200hPa) wind fields give rise to vertical circulation patterns that impact on JJA rainfall and errors in the wind field arising from the SAM region will thus contribute to errors in African rainfall.

The second diagnostic is the Potential Vorticity (PV) tracer technique developed at University of Reading (Chagnon et al 2012, Gray et. al 2014), which focuses on evaluating local physical processes in the MetUM (e.g. convection, boundary layer (BL) mixing) and their impact on the evolution of the flow as characterized by the PV. The evolution of PV is conserved following the flow (equation 1), unless there is diabatic heating (second term on right hand side of equation 1) or frictional forcing (first term) operating.

$$\frac{dPV}{dt} = \frac{1}{\rho} F_\zeta . \nabla\theta + \frac{1}{\rho}\zeta . \nabla\dot{\theta} \qquad (1)$$

The PV tracer technique allows us to accumulate the contributions to the diabatic and friction forcing terms from the MetUM parameterisations (e.g. convection, BL mixing, gravity wave drag). We can then contrast the evolution of the PV in the analyses and in a free running simulation/forecast and try to ascribe errors that arise in the forecast PV evolution to specific physical processes using the PV tracer budget equation.

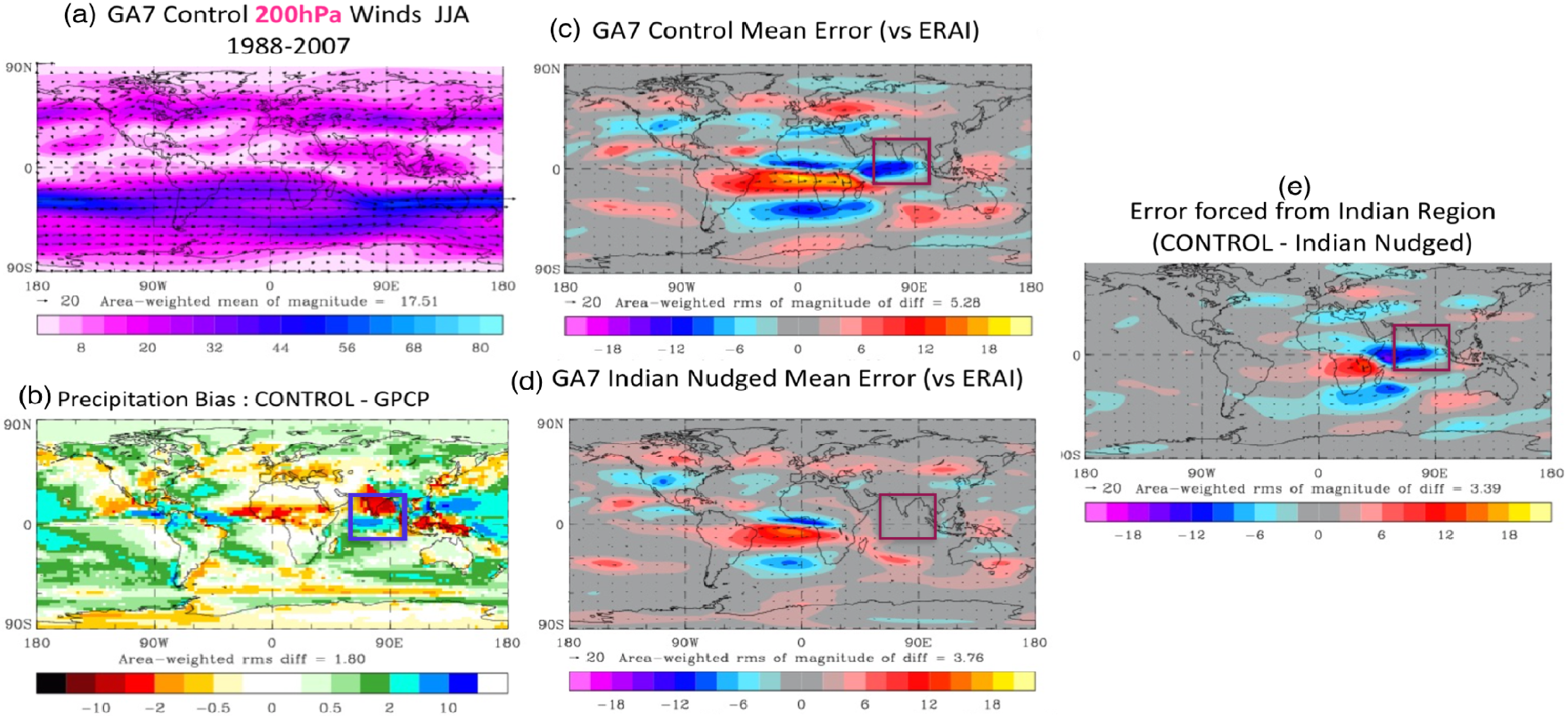


Figure 5: Impact of nudging in the South Asian Monsoon (SAM) region on African circulation during June-August (a) 200hPa wind field from N96 AMIP CONTROL simulation 1988-2007, (b) Precipitation biases (CONTROL - GPCP). The SAM domain used for nudging is shown, (c) Total mean error in 200hPa winds (CONTROL - ERA-I), (d) as (c) but for SAM nudged simulation, (e) Error forced from SAM domain. The colours in (c), (d) and (e) show the error in the wind speed, where negative (positive) indicates too low (high) relative to observations. As expected, errors vanish where corrected (within the red box – (d)), but are also greatly reduced over most of sub-Saharan Africa – showing remote linkage. This is important because the errors impact the tropical easterly jet which is known to be associated with production of rainfall in the June-September season across West, Central and parts of East Africa. To correct model errors, it is important to know their source – and this work has revealed one important source.

Next steps:
More detailed study of climate variability and teleconnection responses in nudged runs will be undertaken and other regional nudging domains considered to explore e.g. the role of extratropics, tropical Atlantic, South America, and East Pacific/ENSO on African model error and climate variability. The nudging sensitivity to relaxation timescale and model resolution as well as uncertainties in re-analyses in tropics may also be explored.

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

WP1.2a The role of model resolution and coupled processes; and WP1.2b Process-based evaluation of biases in the mean and teleconnection pathways

These sub-workpackages aim to understand the sensitivity in the final response to remote drivers to (a) air-sea coupling and (b) horizontal resolution. Work this year has been described under related activities in WP1.1b using the coupled and uncoupled MetUM versions at N96 and N216 resolutions – as listed in Table 3.

WP1.2c Regional circulation, thermodynamic and internal dynamics responses to teleconnections

Last year work focused on developing a methodology for diagnosing how local rainfall processes and variability respond to external forcing and quantifying the relative role of these local processes. Spectral analysis of time series of rainfall, local diagnostics and metrics for remote forcings, involving transformation into a frequency domain, was developed.

This year resource under this deliverable has been temporarily shifted to WP2 (haboob parameterisation). Work has now restarted and next steps include:

- Analysing Outgoing Longwave Radiation from the driving global model run to characterise the tropical waves modes and document them in a database.
- Using this database of tropical waves to search for their counterpart within the 25km and 4km runs over African and identify the local response to these waves (e.g. coupled responses in rainfall and moisture convergence over the Sahel).

Progress against deliverables:
Deliverable D1.1a, January 2017: Submitted peer-reviewed paper on the role of large-scale hemispheric processes and model biases on the simulation of the West African Monsoon, including the specification of process-based diagnostics for evaluating models.

This deliverable has been achieved with three peer-reviewed papers now published (Haywood et al. 2016, Hawcroft et al. 2016 and Stephens et al. 2016) – see work under WP1.1a above. A further paper is near submission with contributions to an ongoing model intercomparison project likely to yield 3-4 papers prior to the end of the project. Planned work evaluating a perturbed parameter ensemble of the latest Hadley Centre model should yield a further publication.

Deliverable D1.1b, December 2017: Submitted peer-reviewed paper(s) detailing the MetUM performance for Africa teleconnections in the CMIP5 context with a focus on the relative role of overturning-type circulations and wave activity from remote tropical biases on teleconnections to Africa. Demonstration of the impact of diabatic heating bias correction from idealised and nudged experiments in key regions on African climate variability.

The results described in the section are contributing to the above deliverable which is on target.

Deliverable D1.2a, March 2018: Submitted peer-review paper on the impact of resolution and ocean/atmosphere coupling on MetUM teleconnections

The work described under WP1.1b is contributing to this deliverable and is on target.

Deliverable D1.2b, March 2018: Submitted peer-review papers (1) describing new techniques for processed-based evaluation of teleconnections; (2) associated paper assessing processes responsible for SST errors and suggesting model developments needed to improve SST errors in the MetUM.

Deliverable D1.2.c, May 2018: Submitted peer-reviewed paper on water and energy budgets and links to African circulations, in response to teleconnections from various sources and phases, in comparison to observations including the relative roles of the Saharan heat low, diurnally driven convection over land, surface coupling and aerosols on impacts of teleconnections over Africa.

This work is scheduled for the coming year, 2017/18.

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

Last year improvements to the MetUM convection scheme were developed and tested that, using physically-based closure principles, make for a more realistic, slower build-up of convective storms. The scheme was found to successfully delay the modelled peak in the diurnal rainfall cycle – which currently occurs too early in the day in global models, and to improve the representation of African Easterly Waves which are an important modulator of rainfall in West Africa.

This year the improvements referred to above have (under WP4) been incorporated in MetUM version GA8, to be released in Spring 2018. Moreover, very good progress has been made on a number of further major changes to the UM convection parameterization, directed at addressing some other long-standing problems with the scheme. These include addressing: a) “timestep intermittency”; b) a tendency to trigger convective rainfall too homogeneously and c) “scale awareness” issues, as discussed below. Tackling these issues represents a very significant step forward towards improving the UM performance both over Africa, and in the tropics more generally.

Addressing timestep intermittency in convection

The existing scheme tends to “switch on and off” from one timestep to the next in an unphysical way. It triggers convection based on whether a lifted parcel can overcome the Convective Inhibition (CIN), but determines the mass-flux and rainfall rate using a separate parcel ascent and “convective closure” calculation based on Convective Available Potential Energy (CAPE). The scheme is intermittent because the convective heating from one timestep typically increases the CIN so much that convection can’t trigger at all on the next timestep. A number of inconsistencies between the triggering and closure calculations were identified and addressed, and crucially the closure has been rewritten with an improved numerical scheme which implicitly accounts for the increase in CIN due to the convective

heating. This was found to remove most of the timestep intermittency of the convection scheme.

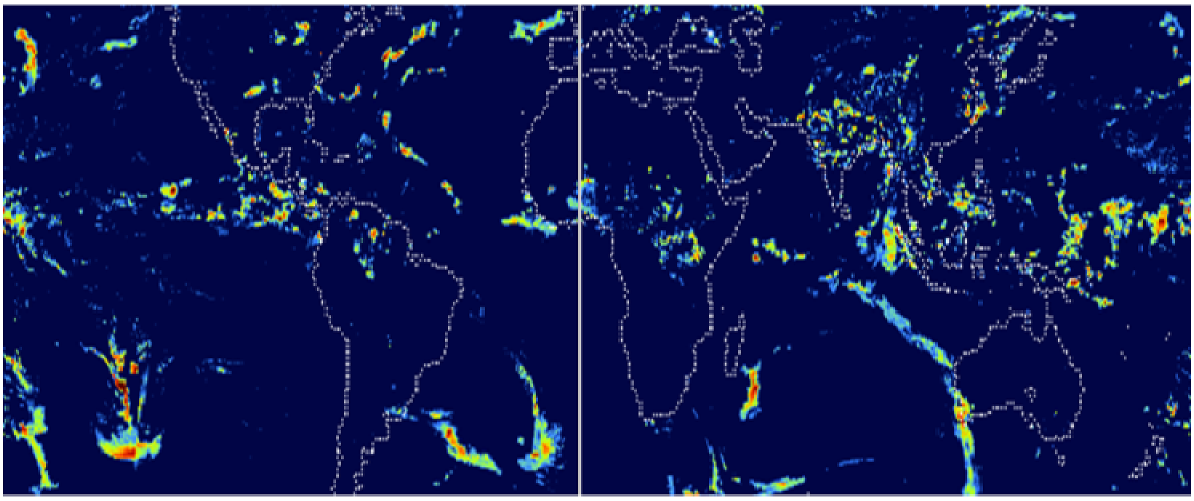
Addressing the over homogeneity in model convective rainfall

When averaged over one or two hours, the global UM tends to produce too-light convective rainfall over much too large an area. This is true over the tropical oceans generally, and over tropical land during the day. This is because the convection scheme lacks representation of processes that cause convection to occur more easily where pre-existing deep convection is already occurring (e.g. forced uplift by cold-pools). This is already partly addressed at GA8, with the introduction of a new convective prognostic field (reported on last year), which reduces the dilution of convecting parcels by the environment (the entrainment rate) where convective precipitation has recently occurred. A further modification has been tested, in which the parcel kinetic energy (KE) used to overcome the CIN is increased as a function of the same prognostic, promoting more persistent triggering of convection. This has yielded dramatic improvements in the organisation of parameterized convection in global UM tests, with much less widespread but heavier, more persistent rainfall in the tropics. An example of the changed character of tropical rainfall with the new scheme is shown in Fig. 6. In a further development, a prognostic cold-pool model is being implemented in the UM (see Section 4.2(b)), which will calculate the triggering kinetic energy used in this scheme in a more physically-based way.

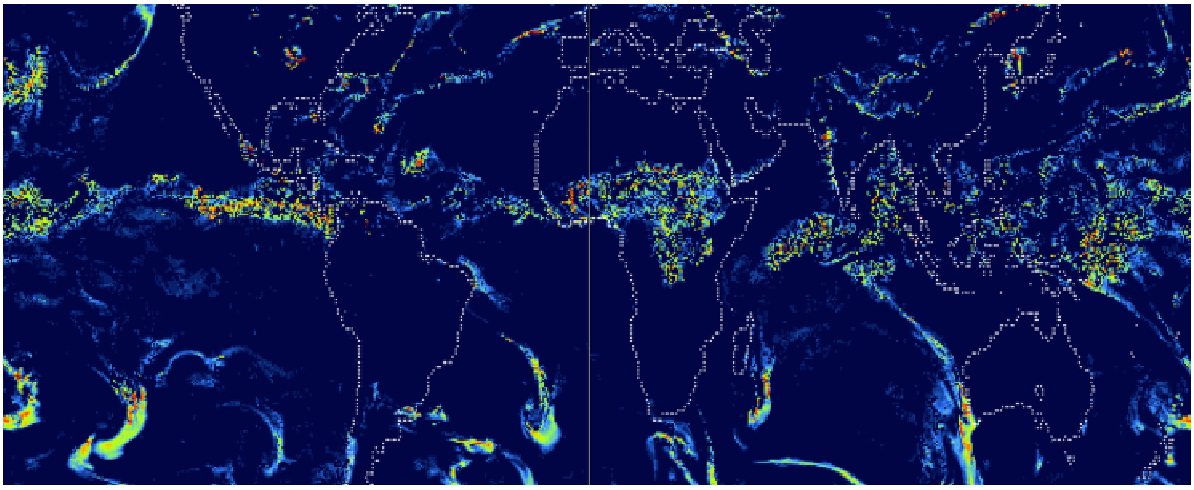
Introducing scale-awareness in the convection scheme

In the CP4-Africa 4.5km convection-permitting model the convection parameterisation scheme is switched off and convection is modelled through a more explicit representation of the physical processes. However, even at 4.5km smaller-scale processes (e.g. updrafts) are not well resolved and this leads to some deficiencies in the representation of convection. The existing UM convection scheme is not appropriate for representing the smaller, unresolved updrafts in these models because it is designed to represent the whole spectrum of cumulus updrafts (including the deep convective storms which are resolvable in, for example, CP4-Africa). It therefore degrades the performance if used in convection-permitting models, producing much too widespread light rainfall as described above. To allow its use in CP4-Africa (in test mode), the convection scheme has been modified to make the triggering of parameterized convection scale-aware and stochastic. At higher resolution, more of the over-turning in the boundary layer is resolved, so that the sub-grid KE available for triggering sub-grid convection is reduced. The amount of sub-grid KE also becomes more unpredictable, as we expect only a small sample of over-turning cells per grid-box. This motivates a stochastic treatment in which the parcel KE used for triggering convection is drawn from a probability density function (PDF). As the model grid-size decreases, the mean of the PDF is reduced, but the variance increases relative to the mean, so that the triggering of parameterised convection becomes less likely but more sporadic. Initial tests incorporating this modified convection parameterization in convection-permitting simulations over the UK show improved onset of small showers, more realistic organisation of convective storms / squall-lines, and reduced “blobbiness”. The next step will be to test the scheme over Africa, using both the CP4-Africa framework and the Met Office operational forecast model for East Africa.

TRMM



GA7



GA7 + prototype GA9 convection scheme (including developments reported here)

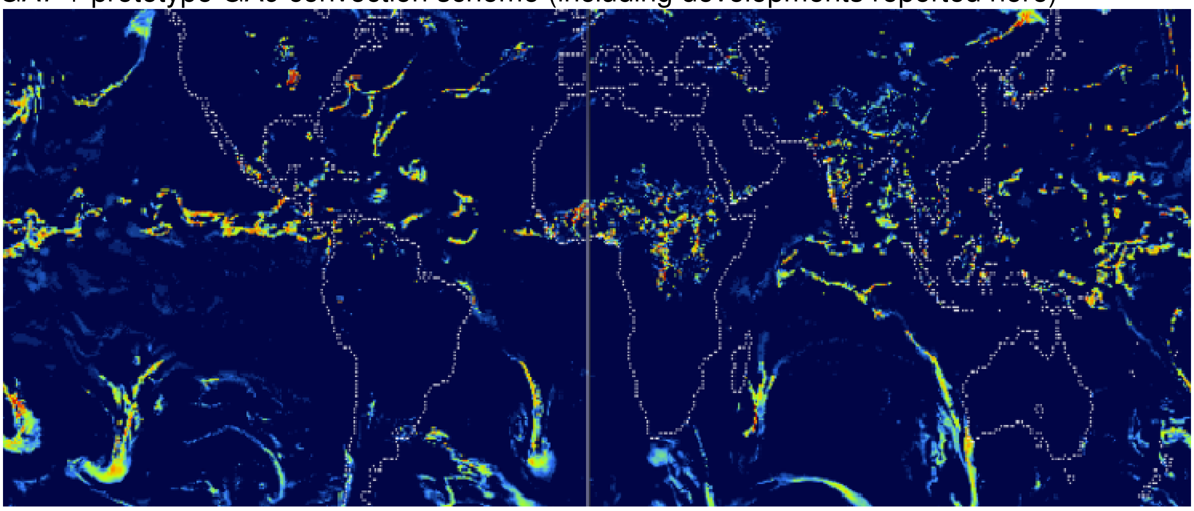


Figure 6: Snapshot of instantaneous surface precipitation rate on day 5 of a global N320 forecast test; (top) observed precipitation from TRMM satellite-based estimate, (middle) GA7 control forecast, and (bottom) a forecast with the modified convection parameterization. Note excessive area with rain, over Africa and other regions in (b) and improved clustering of rain cells in the same places in (c).

b) Understanding convective cold pools

Using the Met Office Large-Eddy Model (LEM), an initial study (Rooney 2015) of the fluid dynamics of single-phase cold downdraughts has yielded estimates of the size and intensity of the cold pools they produce. Last year it was shown that these flows obey self-similar scaling to a good approximation, a necessary step in designing parameterisation.

This year, following the self-similar scaling approach, the first steps have been taken in creating a cold-pool parameterisation. The approach has been adapted for use in a grid-based numerical model, in which information on flow origins is not retained, and cold-pool interaction is expected. Thus, approximations have been introduced to enable the incremental evolution of an existing, evolving field of cold pools to be calculated. This field is forced by convective downdraughts, and dissipates over time if the forcing is removed. In some ways it resembles a physically-based cellular automaton. The model has been coded and tested in a stand-alone configuration (Fig. 7), and an initial Unified Model implementation has been added to the MetUM code repository.

It is possible that the model could be also adapted to represent similar flows in different contexts, such as dust storms, dispersion of dense gases, or the spread of convective anvils.

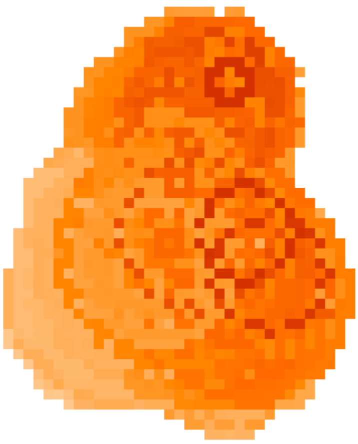


Figure 7: A snapshot of the buoyancy of a 2D field of cold pools in the stand-alone model, forced by a group of moving downdraughts. Darker colours indicate colder (more negatively buoyant) air.

Next steps:

While the scheme is already showing considerable promise, some further modifications are planned shortly. These include:

- Incorporating a new prognostic cold-pool model (see (b) above) into the scheme;
- Improving the treatment of convective cloud;
- Allowing the convective heating profile to adapt more in response to upper-level instability, via “adaptive entrainment”. Getting the shape of the convective heating profile right is thought to be important for simulating large-scale tropical waves, such as the MJO.

A comprehensive set of tests are being planned to evaluate the modifications, and tune the model, with the aim of including the revised scheme in the GA9 global model configuration – due for release in spring 2019.

c) The CP4-Africa simulations

Last year work focussed on the design, development and testing of the convection permitting pan-Africa simulation CP4-Africa simulations. The design includes a ~4.5km horizontal grid length and use of the latest model physics and revised Africa soil properties. Global model simulations at 25km resolution that will drive the CP4-Africa experiments for both present and future climates were also designed and started. Regional experiments for the same domain as CP4-Africa but with parameterised convection and at 25km (nCP25-Africa) were also designed as control simulations. Initial tests of CP4-Africa indicated, as expected, greater realism in clustering and intensity of convective cells.

This year testing was completed and present-day climate simulations have been started and (in January 2017) had completed 4 years of simulation. Evaluation of these simulations has started - although the number of simulated years is currently short and thus results are preliminary. Three years of seasonal means have been created from the first 3 years 2 months of the run and compared with means from the same period from the nCP25-Africa regional control run. Comparison of seasonal mean rainfall for June-July-August (JJA) and December-January-February (DJF) show the CP4-Africa simulation has reduced rainfall biases over land. For JJA, CP4-Africa has increased rainfall over the Sahel and Guinea Coast relative to the 25km control (Fig. 8b), leading to near removal of the large dry biases evident in the control (compare Figs. 8c&d). In other parts of Africa biases are generally similar to those in the control run, with an indication of a slightly wider area of wet bias in the Congo Basin. Over adjacent ocean regions CP4-Africa and nCP25-Africa errors are broadly similar, though CP4-Africa has a wet bias (as opposed to the nCP25-Africa dry bias) along the Gulf of Guinea coast. There are large changes in the mean top of atmosphere radiation fields over the region of precipitation, changing the sign of many biases (not shown). The CP4-Africa simulations have far more cloud ice and water in the regions of convection explaining the changes in the radiative fields.

Examination of the variability in the CP4-Africa simulation shows many changes for the better. The propagation of meso-scale systems westwards with African Easterly Waves (AEWs) is improved (Fig. 9). The westward propagation manifests as lines sloping from left to right in the observed time/longitude graphic of Fig. 9c. This characteristic is much more evident in CP4-Africa (Fig. 9a) relative to the nCP25-Africa control (Fig. 9b). A second, weaker, feature of the observed time/longitude graphic (Fig. 9c) is the signature of horizontal linear patterns – these represent the local diurnal cycle or rainfall. This pattern is far too prominent in nCP25-Africa in which a convective diurnal cycle (with erroneous phase, see below) dominates over activity associated with westward propagating systems. The CP4-Africa run has a much more realistic partitioning of activity associated with the diurnal cycle and westward propagating systems – though the diurnal cycle is still too strong.

Further analysis (not shown) finds that the nCP25-Africa control has a very strong diurnal cycle of convective precipitation with the precipitation starting far too early in the day. In the CP4-Africa simulation the precipitation starts later and continues through the night in better agreement with TRMM. Examination of the intensity and duration of three-hourly precipitation on the same grid as TRMM satellite data shows that the CP4-Africa simulation has more higher intensity, longer duration, events than the 25km regional model – also in better agreement with TRMM (see results from AMMA-2050 analysis discussed below).

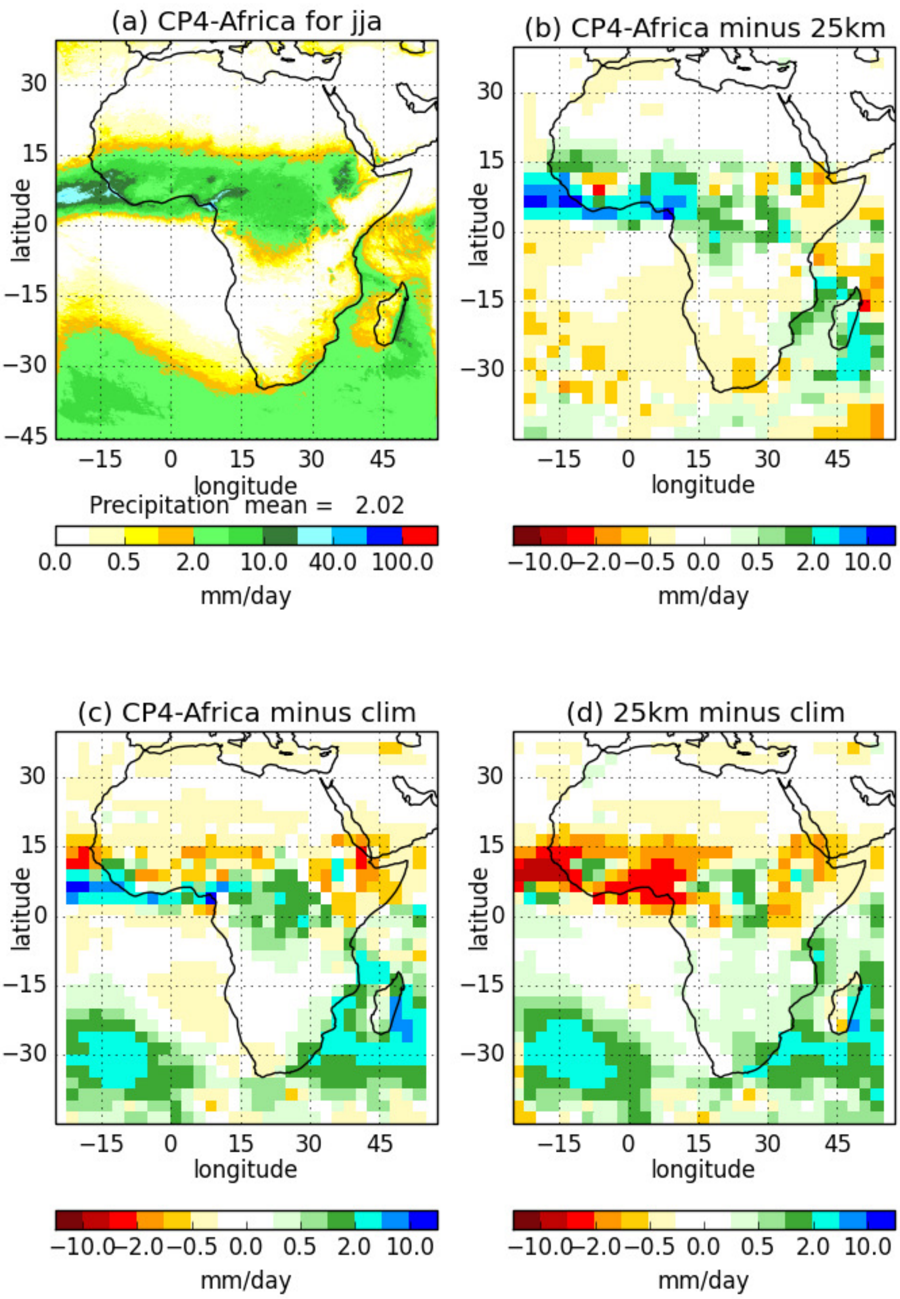


Figure 8: June-July-August 3 year mean surface precipitation for (a) CP4-Africa, (b) CP4-Africa minus 25km, (c) CP4-Africa minus a long term GPCP climatology and (d) 25km regional run minus GPCP climatology.

As reported last year the CP4-Africa simulations are taking longer to process on the HPC than first estimated. The delay is being managed by running two consecutive 5-year periods and making data available as it is generated.

A problem with the initialisation of soil moisture occurred during a restart of the model after a year of simulation. The problem was found during routine monitoring of soil moisture output at CEH (see Section 4.2 for work on land surface modelling). The extent of the impact has been analysed and is largely limited to the deep soil. As a result, an additional run for 1 year starting at the problem point has been run in parallel.

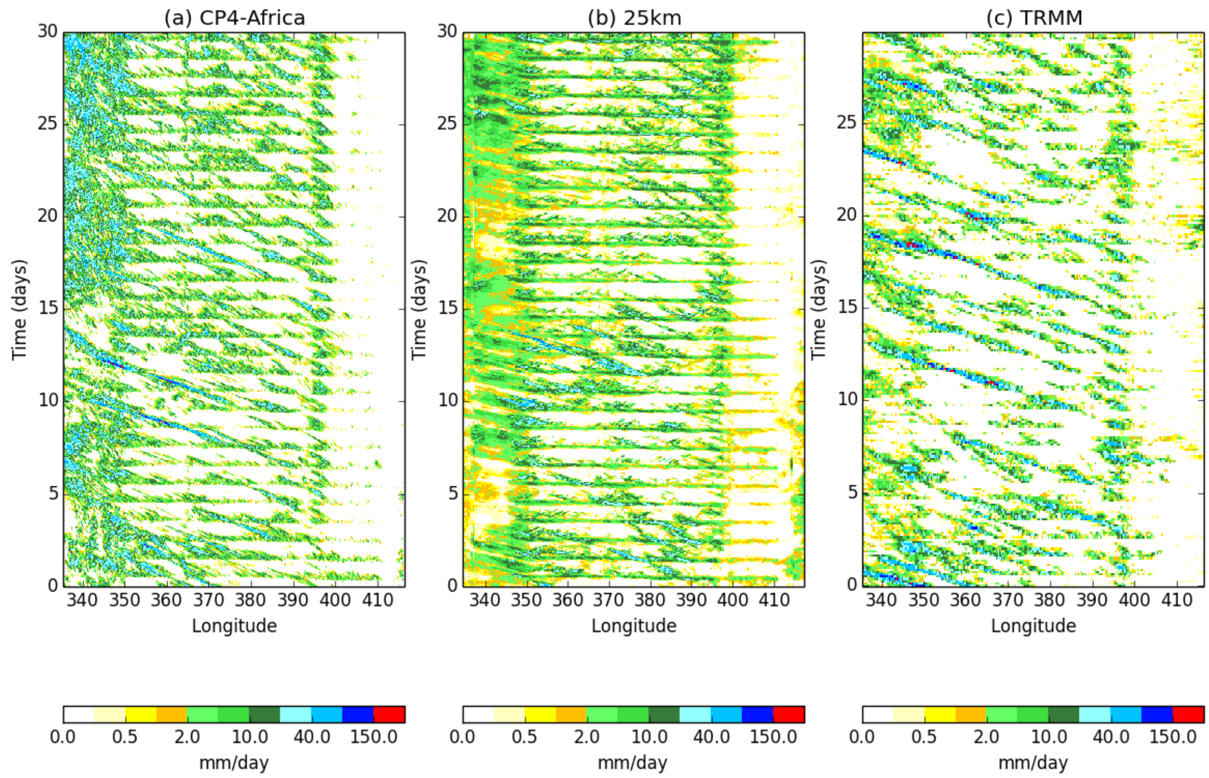


Figure 9: June 1998 Hovmoller (time/longitude) plot for 5-15N, showing improvement in CP4-Africa simulation of systems tracking westwards.

Next steps:
Key priorities are to continue monitoring output from the present day and future simulations (described in WP4), and to complete 10 years with each set. Peer reviewed papers on the technical design of CP4-Africa are in preparation. Regional Consortia have started analysing the CP4-Africa (see below) and will continue to be supported by making the output available on JASMIN.

The CP4-Africa runs will be a major focus for researchers at the mid-term FCFA meeting in Cape Town. Talks and posters will be given and the parallel session on climate science will aim to share information on the CP4-Africa experiments across the FCFA RCs, both to Pillar 1 scientists and to Pillars 2 and 3. Help will be given to others to access the data via JASMIN.

With the strategy of running two 5 year periods in parallel, ten years of simulations (both present and future) will be delivered by mid-2018.

d) Analysis of CP4-Africa simulations in AMMA-2050 and HyCRISTAL

This year has seen first use of the CP4-Africa data in the Regional Consortia AMMA-2050 and HyCRISTAL Pillar 1 activities – as reported below.

AMMA-2050

AMMA-2050 find that CP4-Africa shows a large improvement in the mean West African monsoon state (July-August-September, JAS) with a reduction in the dry bias compared to the global N512 and regional (nCP25-Africa) ~25km models (Fig. 10). This is evident in both the number of wet days and the total seasonal precipitation and is consistent with results discussed in Section 4.2(c) above for JJA.

In 4 study areas of Western, Central, Northern Sahel and the Gulf of Guinea coastal area CP4-Africa exhibits a precipitation intensity distribution that is closer to the observed distribution than the N512(25km) regional control run - with more short duration strong rainfall events (Fig. 11). CP4-Africa also simulates a better timing of the afternoon convection peak compared to N512 and a better representation of wet and dry spell frequency (not shown).

These are substantial performance improvements which make this model more reliable for user-oriented metrics regarding intense rainfall events, wet and dry spells. Areas where biases remain include over orography and over the ocean during the oceanic phase of the monsoon where precipitation is overestimated. Over orography, localised overestimation of rainfall may be seen in wet biases over the Jos Plateau (Nigeria) and Guinea Highlands for example (Fig. 10 bottom right). The number of wet days is still underestimated by 10-30 %, especially on the southern side of the Sahel (note: large percentage wet biases near the northern edge of the rainband in all models partly reflect very low observed rainfall in this region). While improved, the morning rainfall is still underestimated compared to observations and the afternoon peak can be too dominant in some regions: the number of non-organised diurnal convective systems is probably overestimated at the expense of propagating organised mesoscale convective systems but this still has to be confirmed by ongoing research.

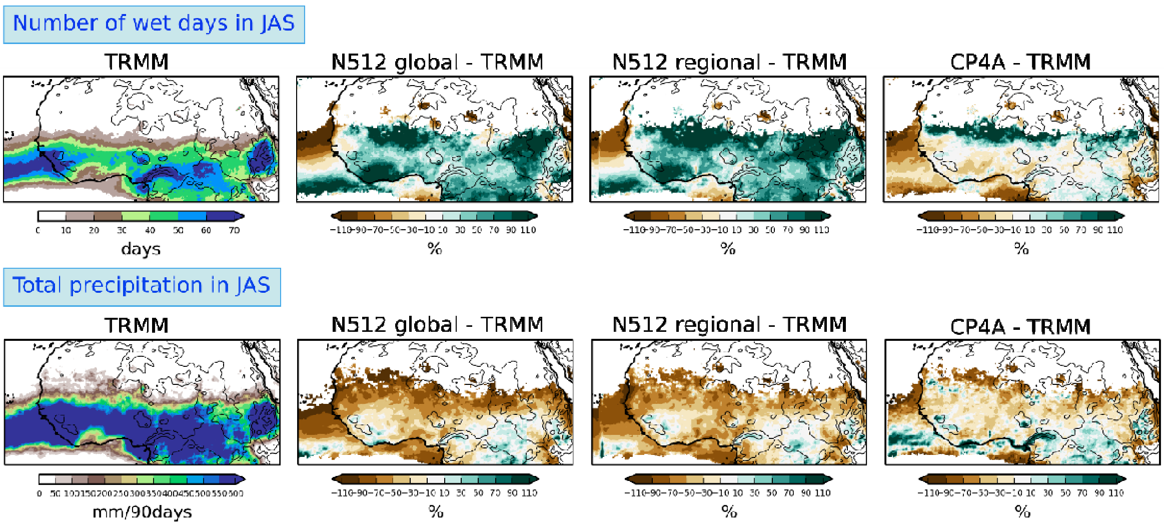


Figure 10: number of wet days (top) and total precipitation (bottom) in the Sahelian phase of the monsoon from July to September. TRMM-3B42 absolute value is shown on the left, the percentage differences of the models with TRMM are shown from left to right: N512 global – TRMM, N512 regional (nCP25-Africa) – TRMM, CP4-Africa – TRMM.

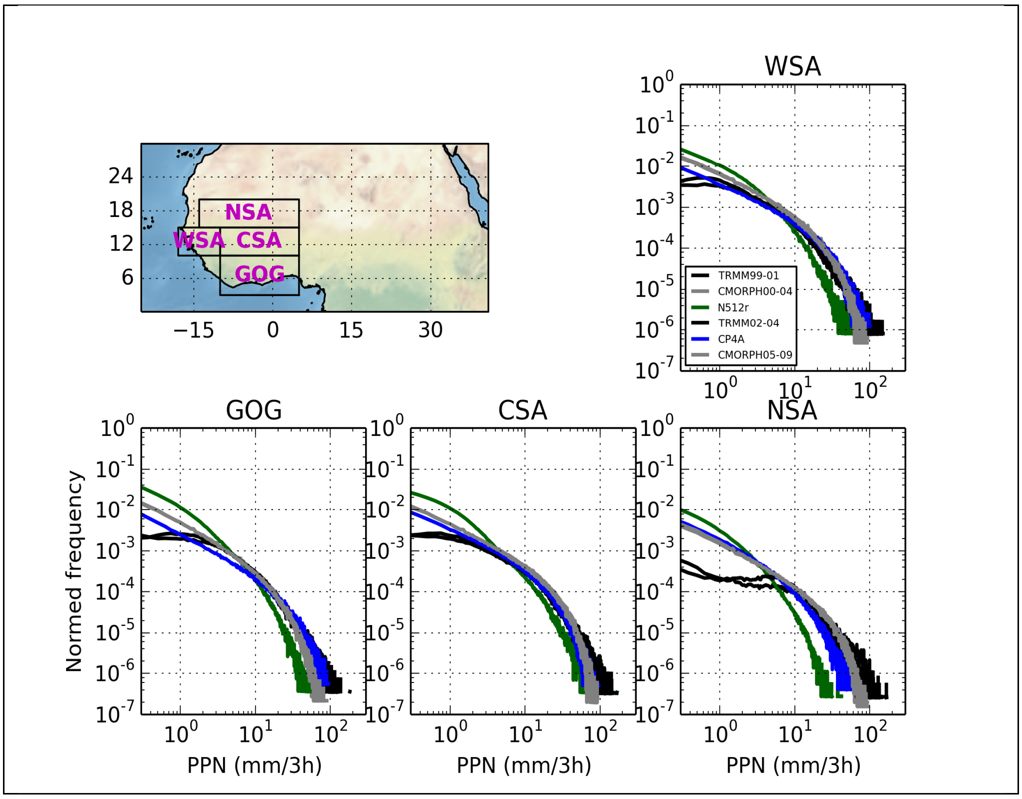


Figure 11: 3-hourly precipitation distribution on all days with regular 0.125mm/3h bins in each region shown in top left corner: Western Sahel (WSA), coast of the Gulf of Guinea (GOG), Central Sahel (CSA), Northern Sahel (NSA) for 2 sets of 3 years of TRMM (black), 2 sets of 3 years of CMORPH (grey), N512 regional (nCP25-Africa - green) and CP4-Africa (blue). *Courtesy S. Berthou (AMMA-2050).*

HyCRISTAL

Generation of storms in East Africa is strongly coupled to the complex topography, Lake Victoria and other lakes, and the Indian Ocean coastline. Convection-permitting simulations from CP4-Africa provide the opportunity to study the effect of these systems on climate in a way that has not previously been possible. Initial results show an improved timing of precipitation, compared to the parameterised convection simulation, over several locations in East Africa including the Lake Victoria basin. There is increased rainfall over Lake Victoria and mountainous regions with the convection-permitting simulation, and this has greatly altered the surface energy budgets. The change in latent heat flux over the Lake shows a particular marked change, and this is likely due to changes in the low-level wind speed. As well as changes to rainfall amount and timing, the convection-permitting simulation shows much similarity with satellite observations with regard to propagation of precipitation features from east to west across the Lake Victoria basin – improving on the performance of the 25km non-convection permitting control simulations Fig. 12. In particular westward propagating activity in CP4-Africa initiated over the central (eastern) rift valley in the morning (evening) are well aligned with those seen in TRMM – though rainfall intensities are too strong. Future work will look to study the climate change impact on the climatology of rainfall and the propagation of storms in East Africa.

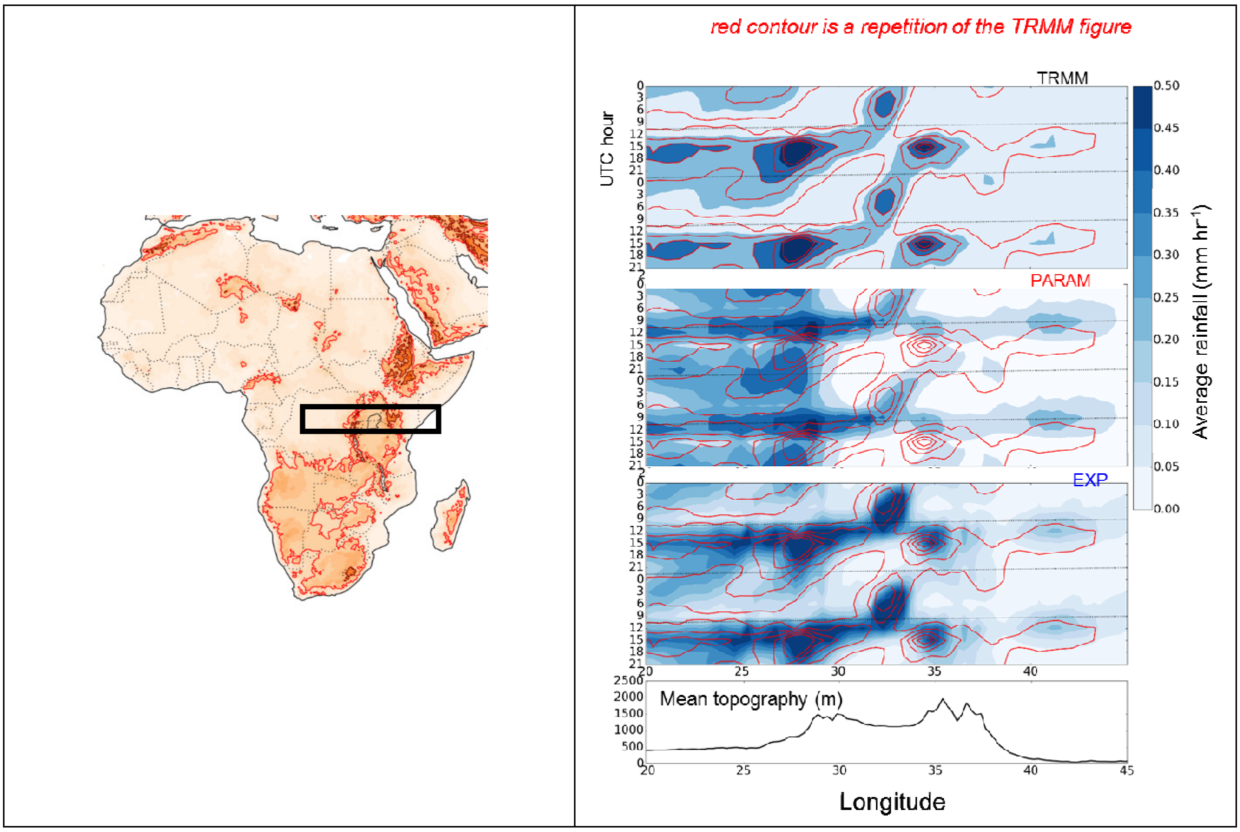


Figure 12: Right: Time/longitude plot of average rainfall (mm/hr) (1998-1999) through the latitude of Lake Victoria (as shown on left) – a 2 day cycle is shown. Row 1: Observations (TRMM), Row 2: PARAM = nCP25-Africa (25km); Row 3: EXP = CP4-Africa (4.5km); Row 4 = orographic height. The red contours for TRMM values are repeated in Rows 2 and 3 for reference. *Courtesy Declan Finney (HyCRISTAL)*

e) Idealised high resolution convective process studies

Understanding the factors which determine the transient behaviour of convection is vital to improving the diurnal cycle of precipitation over Africa. The aim of this section of work is to use idealised high resolution cloud resolving simulations to understand these factors and therefore improve the current parameterisation of convection. These idealised simulations will be performed over a large domain of 500km x 500km at a range of resolutions from ~100m up to 40km.

Work this year has developed tools and techniques that will allow us to fully analyse the high resolution simulations. The Turbulent Kinetic Energy (TKE) Budget is a useful tool for analysing the interplay of turbulent processes influencing convection. Local changes in TKE are determined by vertical wind shear, buoyancy, turbulent transport, pressure fluctuations and dissipation. The budget of these has been analysed for an idealised diurnal cycle case study performed in the Met Office Large Eddy Model (LEM) to determine which terms control the departures from local steady state (Fig. 13).

Next steps: The work will be extended to include the budgets of vertical velocity variance and vertical potential temperature flux. Spectral diagnostics will be analysed to determine the scales for dissipation and production of energy along with upscale and downscale transports.

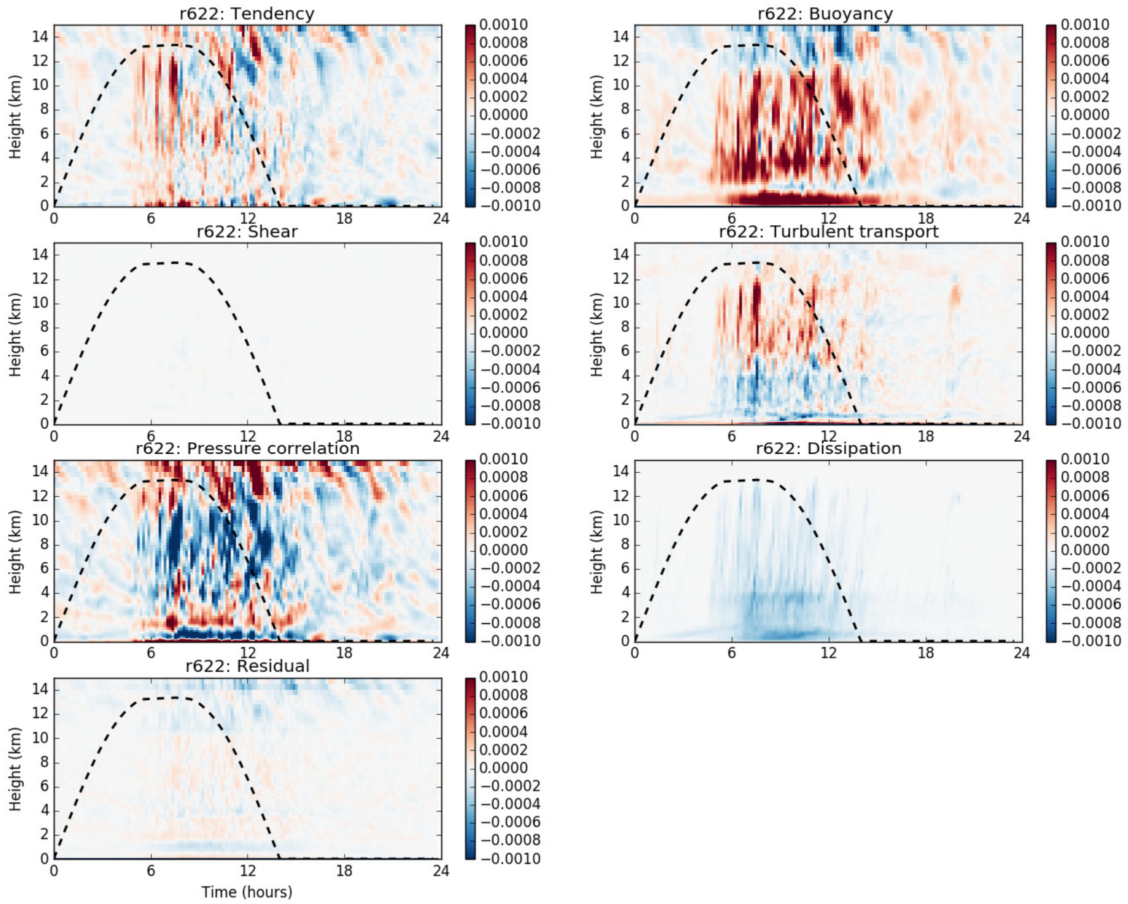


Figure 13: 5-day composite of each term in the turbulent kinetic energy budget. Red/blue colours indicate the production/removal of turbulent kinetic energy. The tendency term (top left) represents local changes in TKE and is the sum of all other terms. The black dashed line indicates the strength of the surface forcing.

W2.2 Land model development

Last year work focused on development of the land surface ancillary datasets required for the CP4-Africa model. This included introduction of homogenised soil properties and associated soil moisture fields for initialising the CP4-Africa runs. Updated land cover fractions centred on the year 2000 were also derived and provide more realistic distribution of forests than previously used IGBP derived fractions.

This year work has been 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.

Interception Loss: Interception loss refers to the amount of moisture that is "lost" to the soil when rainfall is intercepted by the vegetation canopy and rapidly re-evaporated to the atmosphere. Early results from CP4-Africa indicate a dramatic reduction in interception loss (Fig.14a&b) and have highlighted issues in the representation of interception loss. Interception loss is highly sensitive to rainfall intensity and frequency. In comparison to site observations from tropical forest in Amazonia and Ivory Coast (not shown), the parameterised convection scheme produces unrealistically high annual values of interception loss, particularly towards the coastal areas (Fig. 14a). This is due to too frequent

low intensity rainfall i.e. drizzle produced by the model (see Section 4.2 (a)). This has important implications for soil moisture memory (too much interception means soils dry out more quickly in the dry season), and the sensitivity to land cover change (interception loss effectively reduces the influence of root depth and stomatal behaviour on surface fluxes). We hope to address this in collaboration with IMPALA convection scheme research.

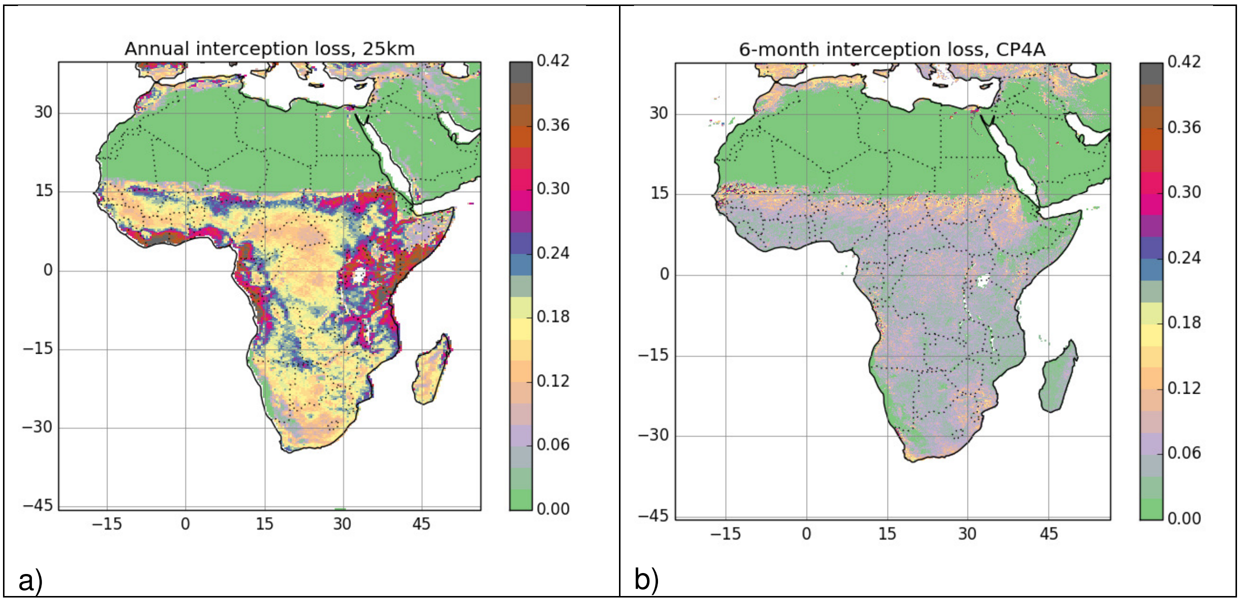


Figure 14: (a) Interception loss from the first year of the 25km IMPALA present-day climate control simulation and (b) for the first 6 months of the CP4-Africa simulation

Root Zone soil moisture: We are currently looking at how rapidly the land surface dries out in the days and weeks after rain across Africa. We are using a new observational technique based on the dynamics of land surface temperature observations (Gallego-Elvira et al, GRL 2016) to evaluate both coupled and offline JULES simulations, as well as other models with appropriate diagnostics in the CMIP5 archive. We hope that this will highlight where and when models provide a credible depiction of soil moisture controls on surface fluxes.

Photosynthesis: How photosynthesis responds to future projections of higher $C0_2$ and temperature is important for the carbon balance (potentially affecting viability of tropical biomes), and also for the regional energy and water cycle. There is large uncertainty in how photosynthesis and stomatal conductance respond to high temperatures, and we are testing, in JULES, alternative formulations of these processes with an improved physiological basis.

Next steps:
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.

Drought deciduous phenology: Building on work to develop the JULES land surface model in previous years, analysis will be performed to evaluate the performance of JULES for simulating the phenology (seasonal cycle) of different plant functional types across regions of transition in Africa. Based on results from this analysis, a simple model of soil moisture-controlled leaf area Index (LAI) dynamics will be developed using satellite data. This will allow JULES to simulate intra-seasonal and inter-annual LAI anomalies in response to rainfall.

W2.3 Aerosols

Dust is known to be important to weather and climate through the modification of the radiation budget, cloud processes, atmospheric heating, stability, circulation and dynamics as well as feedbacks through land and ocean ecosystems. Additionally, in West Africa respiration diseases, some of which derived from dust related poor air quality, are a major cause of child mortality.

a) Improving the spatial distribution of Saharan dust emissions in the MetUM

Last year, a haboob parameterisation scheme was tested and calibrated over West Africa and used to model a full seasonal cycle of haboobs over northern Africa. Results indicate that haboobs contribute one fifth of the annual dust generating winds over northern Africa. Plans were developed to integrate the haboob scheme into the MetUM, linking with parallel IMPALA work on representation of cold pool generation from convective downdrafts. Additionally, work last year focussed on foundation work to improve the MetUM's spatial distribution of Saharan dust emissions through development of a satellite-preferential source mask.

This year work has focussed on testing of the satellite-preferential source mask for improving the MetUM's dust emissions. We have demonstrated an improvement in dust source emission in the UM by homogenising the soil data and scaling emissions using a preferential source term based on the SEVIRI observations. The improvement is defined by comparing aerosol optical depth (AOD) from SEVIRI and the Moderate Resolution Imaging Spectroradiometer (MODIS) with model AOD. However, the emissions scaling leads to a decrease in overall dust emission amounts and, consequently, larger underestimates in atmospheric dust loadings than for simulations without preferential source scaling when compared to AOD from SEVIRI, MODIS and surface-based Aerosol Robotic Network (AERONET) stations. This is because the current dust scheme was originally tuned to minimise bias against data such as AERONET AOD observations. The emissions scaling effectively undoes this tuning; careful re-tuning is therefore required to bring dust emission amounts back in line with these total quantities.

b) Biomass burning aerosols

Continued work this year (leading to Johnson et al. 2016) has demonstrated the improvements made to representation of biomass burning aerosol by incorporation of the new Global Model for Aerosol Processes (GLOMAP-mode) modal aerosol scheme in the HadGEM3 climate model. The scheme predicts the particle size distribution, composition, and optical properties, giving increased accuracy in the representation of aerosol properties and physical–chemical processes. Improvements were demonstrated by comparing HadGEM3 simulations with field campaign measurements including those of the DABEX and SAFARI-2000 campaigns over West and southern Africa respectively.

Next Steps:

Work will continue to implement the haboob dust generation scheme in the UM and this will then be linked to the new convective cold-pool parameterisation. A paper on retuning of the dust emissions scaling through a satellite-preferential emissions mask is in the final stages of preparation. Work will continue on retuning the scheme in preparation for implementation into the MetUM.

Progress against deliverables to 2018:

Deliverable D2.1a, March 2018: Submitted paper based on the high resolution simulations outlining the factors which determine the transient behaviour of convection

The work described in Section 4.2(e) contributes to this deliverable

Deliverable D2.1b, March 2018: Project report on new parameterisations of convection which result in an improvement to the diurnal cycle over Africa.

Achieved early. See Section 4.2(a) of this report and Section 4.2 of the report of the 2015 IMPALA Science Meeting:
http://www.futureclimateafrica.org/wp-content/uploads/2017/05/impala_science_meeting_dec15.pdf

Deliverable D2.2a, July 2017: Submitted paper on evaluation of LST during dry spells across CMIP5 models

Delayed – expected July 2018.

Deliverable D2.3a, June 2016: Submitted paper detailing the performance of the dust model developments against observations and the implications for climate prediction

A project report has been prepared and is available on request – submission of paper for peer review is scheduled for March 2018.

D2.3b, December 2017: Project report detailing the performance of the optimal biomass burning aerosol model against AERONET and satellite observations.

The work described on assessment of the GLOMAP-mode modal aerosol scheme in the MetUM has been published (Johnson et al. 2016) in completion of this deliverable.

4.3 WP3: Metrics and Model Evaluation

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

Last year work focussed on planning and starting the pan-Africa and regional MetUM processed-based evaluation work with IMPALA African partners. These activities included a Model Evaluation workshop at Oxford University in March 2016, attended by 3 of the African partners, at which initial results were discussed and the structure and content of a paper now accepted for the Bulletin of the American Meteorological Society (BAMS) was outlined.

A spreadsheet for accumulating and sharing information on metrics for model evaluation over Africa that are in use and/or being developed within IMPALA was prepared and circulated.

This year work has focussed on finalising metrics and evaluation results and on co-authorship of the BAMS paper, which has now been peer-reviewed and accepted for publication. Work on WPs 3.1, 3.2 and 3.3 has been integrated and progress is reported here in one combined section. The BAMS paper, entitled: “Evaluating climate models with an African lens” lays out a strategy for processed-based evaluation of climate model performance over Africa with examples of MetUM evaluation over East, West, Central and southern Africa as well as at pan-African scale. It also encourages collaboration between model developers and African scientists to deliver a coordinated hub of model metrics for Africa to promote accelerated progress in model development for the continent and draws attention to a WCRP initiative, aligned with this idea, that plans to support development of a community-based toolkit to aid model evaluation across the CMIP model ensemble. In the BAMS paper, example diagnostic tools that could form part of a model evaluation resource hub for Africa are proposed for each region.

Example diagnostics for each region are briefly summarized below. These are presented in the paper as examples of process-based evaluation which might be useful for each region, and as a basis for further discussion about which diagnostics would ideally form part of the CMIP evaluation infrastructure mentioned above.

a) Southern Africa

For southern Africa, the analysis focused on tropical-extratropical cloud bands, or “Tropical Temperate Troughs”, due to their important role in rainfall generation over southern Africa. TTTs are also influenced by a number of other important circulation features in the region and therefore might be a good indicator of the model’s ability to capture the regional climate. A cloud band identification software developed by Hart et al. (2012) was adapted to run on the MetUM, to investigate the number, spatial distribution, and seasonal cycle of TTTs, as well as the relationship with precipitation.

GC2-N216 produces tropical-extratropical cloud bands with a similar spatial distribution to satellite data (Fig.15a). However, the model generates too many TTTs, 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 (Fig. 15b). The most striking contrast between the model and satellite data is in southern winter (June-August): whilst TTTs are a southern summer phenomena in nature (peaking in November), the model also generates TTTs during winter, when southern Africa should be dry (Fig. 15c).

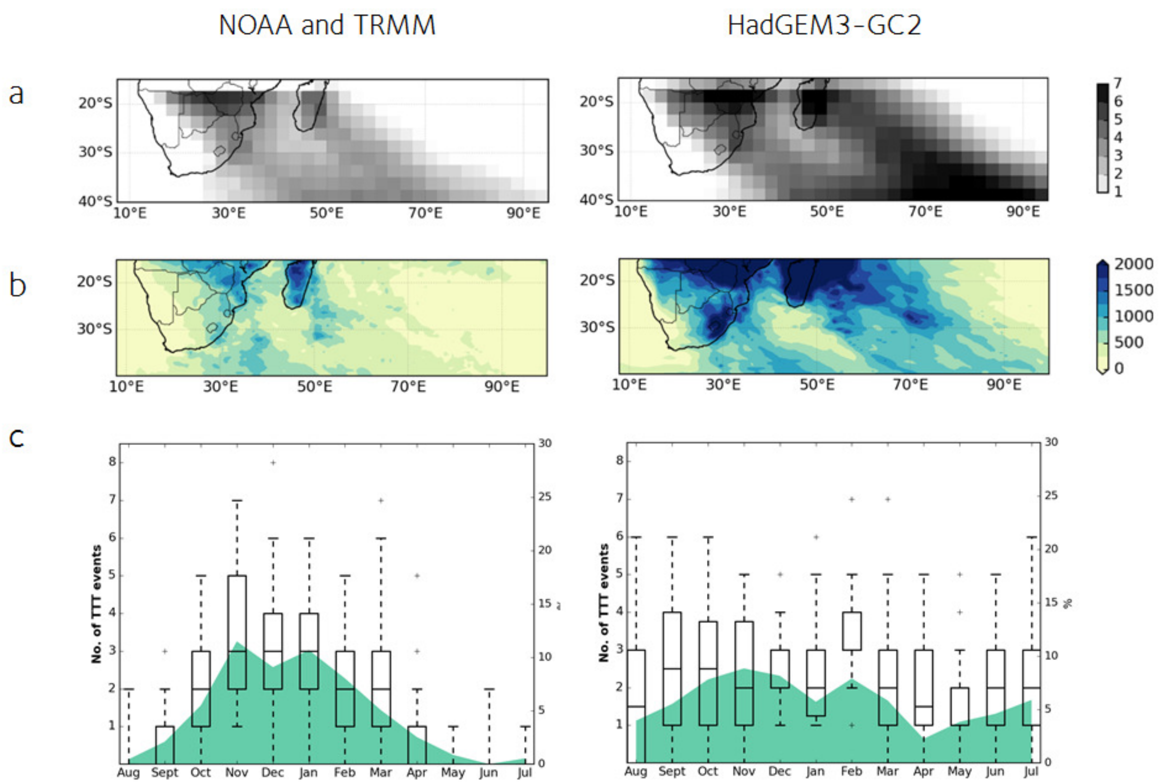


Figure 15: Characteristics of TTT events in satellite data (NOAA OLR data and TRMM precipitation data) and GC2-N216. (a) Gridpoint frequency of cloud bands in December (gridpoint count / year) , (b) sum of precipitation in mm contributed by TTT events in December for 1998-2013, (c) annual cycle of TTTs over the continental domain (7.5-40°E), with boxplots to show the number of events (mean shown in black), and blue shading to show the percentage of precipitation contributed by continental TTTs (based on percentage of total precipitation across the whole domain shown in (a) and (b) – locally TTTs can contribute much higher percentages). *(from James et al. 2017*)

Next steps:
The tools used to evaluate TTTs will be applied to updated model versions (likely GA8/GC4) in year 4 of the project. In the meantime, there is ongoing work as part of the UMFULA project to compare the results from the Met UM with other climate models, including from CMIP5 and CP4Africa.

b) Central Africa

Previous analysis of MetUM biases highlighted a close relation between the spatial pattern of vertical motion and precipitation biases over the Central Africa (CA) region. Broadly, during the rainy seasons from March to May (MAM) and September to November (SON), a dry bias over the north-western CA is related to insufficient convection in the MetUM. Whereas a wet bias in south-eastern CA is related to overestimation of vertical motion. Thus, investigation of drivers of vertical motion over CA may help to define metrics to understand the MetUM precipitation bias.

Spatial patterns associated with vertical motion biases indicate a contribution from large scale circulation. However, well known strong convection year-round over CA suggests that local contributions to vertical motion biases are also important. Therefore, our analysis aims to explore both local and remote drivers of vertical motion over the region. Here, the approach is to explore the contribution of these drivers to the ageostrophic wind field which leads to atmospheric divergence, and in turn vertical motion.

Analysis of remote drivers is performed at mid and upper level with focus on tropospheric jets. During the first rainy season (MAM) mid-level circulation over CA is dominated by the northern component of African Easterly Jet (AEJ-n). Whereas, the second and big rainy season (September to November, SON), is influenced by both AEJ-n and southern component of AEJ (AEJ-s). At upper levels the Tropical Easterly jet dominates the circulation, and is well developed in February and August. These jets are linked to jet streak structure, and the associated transverse circulation is formed by the ageostrophic wind component (Fig. 16).

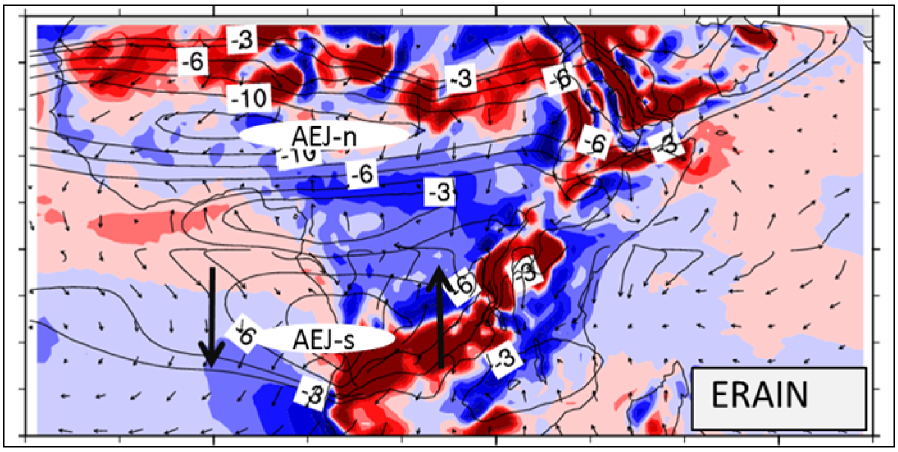


Figure 16: Mean monthly circulation at 600 hPa for October over equatorial Africa from ERA-Interim (ERAIN). Contours indicate zonal wind component, with core speed of AEJ-n and AEJ-s marked. Divergence (convergence) of wind is indicated by red (blue) colour. Vectors indicate ageostrophic motion, with bold arrow underlying transverse motion at entrance and exit regions of AEJ-s.

Local drivers of vertical motion involve diabatic heating. This heating contributes to both inertial advective and inertial diabatic components of the ageostrophic motion.

Next steps: A detailed analysis will investigate the contribution of the mid- and upper-level atmospheric jets, and diabatic heating to modulation of the ageostrophic circulation and

vertical motion over CA. Metrics will be defined and applied to UM outputs to understand model precipitation biases over the region.

c) East Africa

Analysis of the GC2-N216 October-December (OND) climatology over the Indian Ocean region revealed important biases, with the model simulating easterly rather than westerly mean flow over the equatorial sector (Fig. 17a). Despite these errors in the mean state the GC2-N216 has a good representation of interannual variability in moisture flux. Fig. 17b shows composites of the 5 wettest minus 5 driest years over East Africa, based on GPCP and modelled precipitation. The pattern is relatively similar for the model and reanalysis. During wet (relative to dry) years there is more moisture convergence over East Africa and the western Indian Ocean, and less over the maritime continent, with easterly moisture flux anomalies over much of the tropical Indian Ocean. The extent of the wet and dry regions differs between the model and reanalysis but the character of the response is similar.

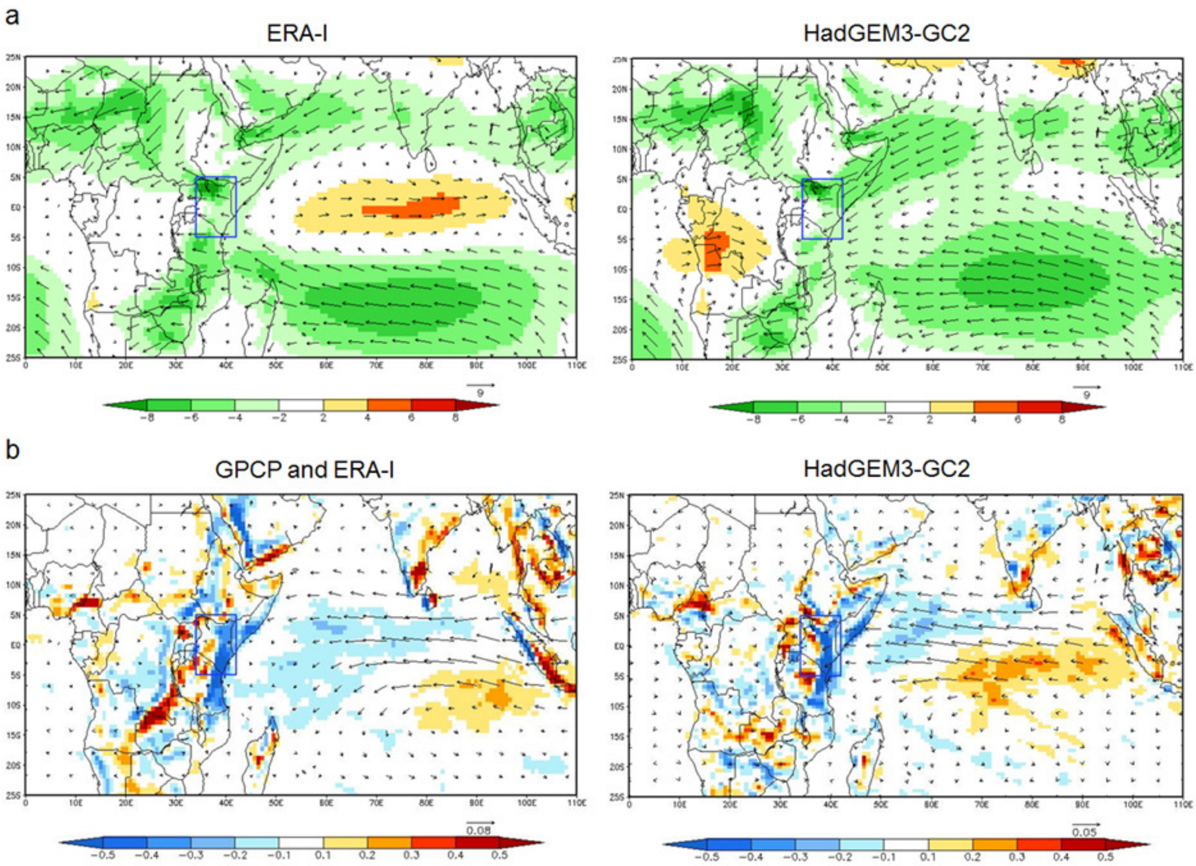


Figure 17: October-December circulation at 850hPa in ERA-I and GC2-N216. (a) climatological winds with contours of zonal wind speed (m s^{-1}) (b) moisture flux (kg kg^{-1} m s^{-1}) with contours of moisture flux divergence (kg kg^{-1} s^{-1} x10^{-7}), for composites of wet minus dry years in East Africa (34-42°E, 5°S-5°N; illustrated by the blue box) as computed from GPCP precipitation for ERA-I and modelled precipitation for GC2-N216. (*from James et al. 2017*)

d) West Africa

The analysis found important differences between the model and reanalysis climatology over West Africa in August, the core of the West Africa Monsoon season. GC2-N216 underestimates precipitation in the Sahel, placing the precipitation maximum over the Guinea Coast (shown in green Fig. 18a). This is also associated with differences in vertical velocity and zonal wind relative to reanalysis. In ERA-I, there is a large region of upward motion throughout most of the troposphere 5-15°N (in blue), situated between the core of the

AEJ (at 600hPa and 14°N), and TEJ (at 200hPa and 7°N). In contrast, GC2-N216 has several regions of upward motion, with a maximum at the Guinea Coast, and a weaker zone of ascent at 10°N. There is strong upward motion in the Sahel, but only in the lower troposphere, and this is capped by subsidence aloft (red shading), perhaps indicative of a SHL, but displaced south relative to reanalysis and disconnected from another zone of ascent at approximately 23°N. The AEJ is too far south, and the TEJ is not clear, indicating a different upper atmosphere flow to ERAI. This could be closely related to the differences in vertical velocity, particularly at the jet exit regions, which are associated with vertical motion.

During wet years (Fig. 18c), GC2-N216 shows more precipitation and more ascent, especially at 10°N, and Hovmuller plots of precipitation suggest that there is a muted monsoon "jump" (not shown). This is still weaker than in reanalysis, but in August the model does show some of the same distinctions between dry and wet years as ERA-I (and NCEP1, not shown). Dry (relative to wet) years are associated with downward anomalies 8-15°N, and a southward shift and strengthening of the AEJ. There is also anomalous ascent near the surface of the Sahel, which could indicate a southward shift of the SHL. This is much further south in GC2-N216 relative to ERA-I, suggesting some differences in terms of the mechanisms for drying.

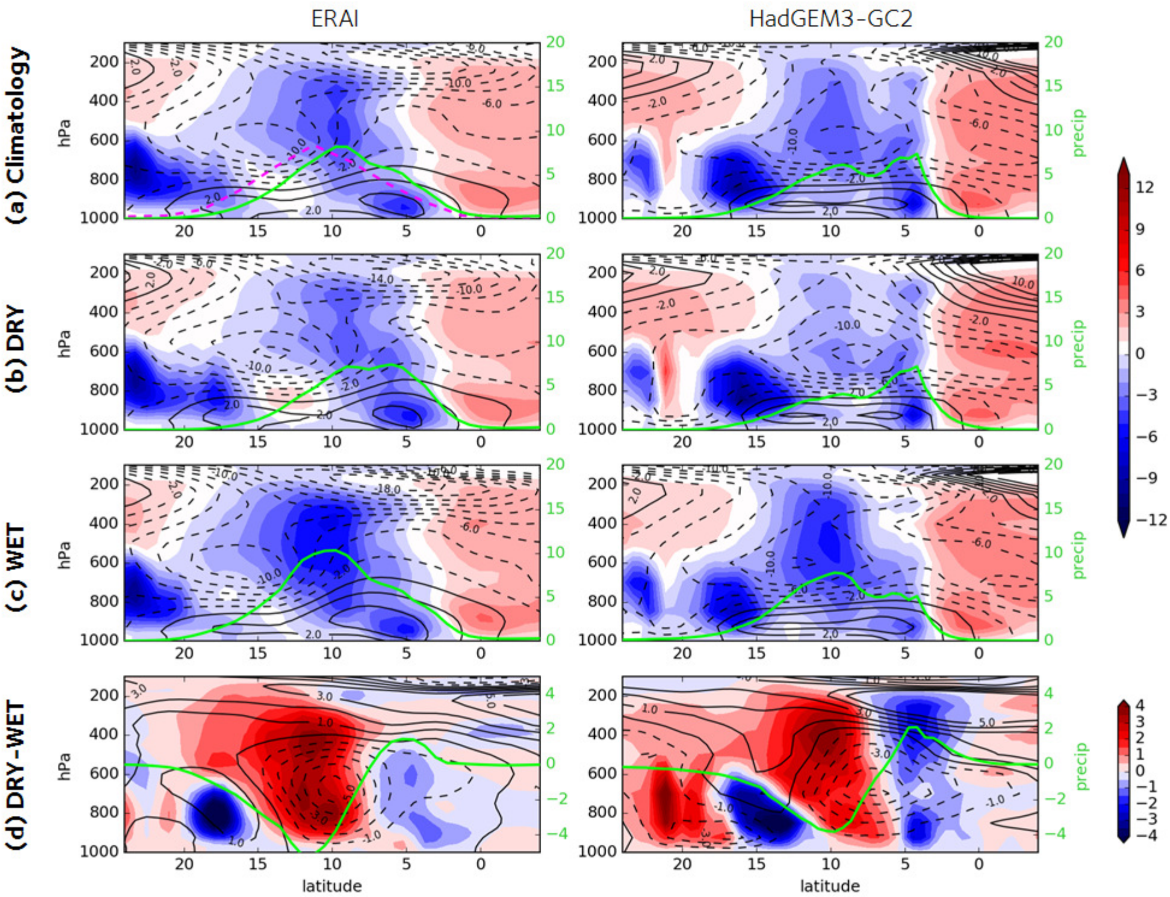


Figure 18: Latitude-height cross sections of vertical velocity (hPa s^{-1}) (shaded), zonal wind (contours, westerly solid lines, easterly dashed lines, m s^{-1}), and precipitation (green lines, mm day^{-1}), averaged 8°W to 8°E during August, for ERA-I (left column) and GC2-N216 (right column). (a) climatological means (GPCP precip is also shown by the pink dashed line) (b) dry and (c) wet composites, and (d) dry composite minus wet composite. (*from James et al. 2017*)

Next steps:
The tools used in the baseline evaluation of the MetUM as reported in the BAMS paper will be applied to updated model versions in year 4 of the project. Planning activities for this second phase of evaluation will include discussions at the mid-term FCFA meeting in Cape Town. Preparations to engage ECRs in evaluation work, starting in 2018 at African partner organisations, will continue through the IMPALA SCD plan.

Progress against deliverables to 2018:

D3.1: June 2016: Submitted paper on metrics and model evaluation in Africa
Achieved: The paper "Evaluating climate models with an African lens" has been submitted an accepted for publication after minor revisions and includes assessment of baseline capabilities

D3.2, Dec 2016: Project document on baseline capabilities of the UM over Africa
Achieved: a summary of Africa-wide performance evaluations for GA7/GC3 and GA6/GC2 has been prepared ("GC3/GA7 assessment: African processes", Tomassini et al.) and is available to FCFA Pillar 1 researchers at:
http://collab.metoffice.gov.uk/twiki/pub/Support/UMUserWorkshop2016/UMuser_Africa.pdf

Next deliverable is D3.3 (February 2019): Submitted paper on improvements to the MetUM resulting from IMPALA science.

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

WP4.1 Model Integration and Improvement

Last year activities focussed on foundational work to increase understanding of processes that give rise to specific biases in MetUM simulations, focusing on the role of resolution and model dynamics and with a regional focus on West Africa, African Easterly Waves (AEWs) and the African Easterly Jet (AEJ). In addition, a comprehensive study of predicted climate changes over Africa, across a wide range of impact-relevant variables, was conducted for the MetUM (GC2) using $4XCO_2$ scenarios. These studies form a baseline against which to measure the impact on climate change signals of Africa-specific model improvements developed in IMPALA.

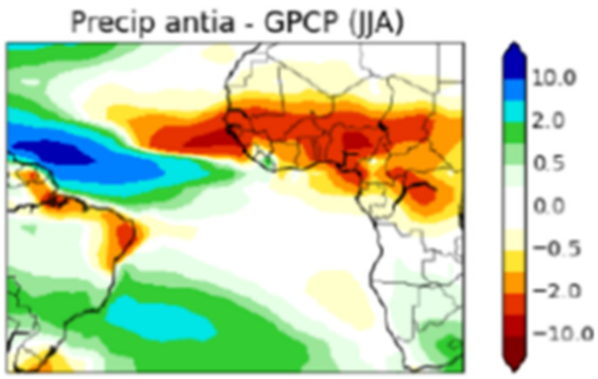
This year work has focussed on assessment of the impact of model changes incorporated into version GA7 of the MetUM. Example results for the West African Monsoon season are shown in Fig. 19. The dry bias in precipitation is slightly improved at GA7 relative to GA6 (cf. Figs 19a and 19b), particularly in the high resolution (N216) version (Fig. 19c). Other biases associated with ITCZ rainfall over the tropical Atlantic are also slightly improved.

To help maintain such improvements in future model versions it is important to improve understanding of the model's representation of key rainfall processes – so the impact of proposed future changes on these processes can be tested. In this context a focus study for West Africa has been conducted in which the interaction between moist convection and the atmospheric circulation in African Easterly Wave (AEW) propagation was investigated in detail – AEWs are a fundamental feature of the West African Monsoon and trigger a substantial proportion of the total rainfall. Both long-term climate simulations as well as MetUM short-range forecasts of a strong African Easterly Wave in July 2010 were examined. Figure 20 shows composites of precipitation based on an objective AEW tracking method applied to ERA-Interim reanalysis and TRMM rainfall observations (left panel) and the

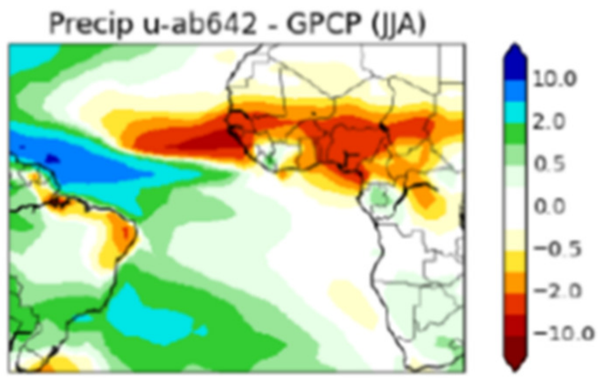
Unified Model (right panel). In the ERA-Interim/TRMM data, rainfall is more closely aligned with the AEW trough. The associated latent heating can thus sustain the wave propagation more effectively than in the model's representation. The study has been submitted for peer-reviewed publication (Tomassini et al., 2017).

Next steps: IMPALA science developed in WP1 and WP2, including – as appropriate - improvements to the convection scheme reported here, will be incorporated into the next releases of the MetUM (GA8 – 2018 and GA9 2019). Evaluation of the performance benefits from these consolidated changes will continue to be documented.

A peer-reviewed paper describing the results of the AEW study has been submitted in May 2017. Moreover, in the coming year we plan to take advantage of the CP4-Africa 4.5km resolution simulations in order to better understand mechanisms of convective organisation and the interaction between mesoscale convective systems and the atmospheric circulation over West Africa. Activities in this work package will continue in close liaison with the parameterisation development undertaken in WP 2.1.



a)



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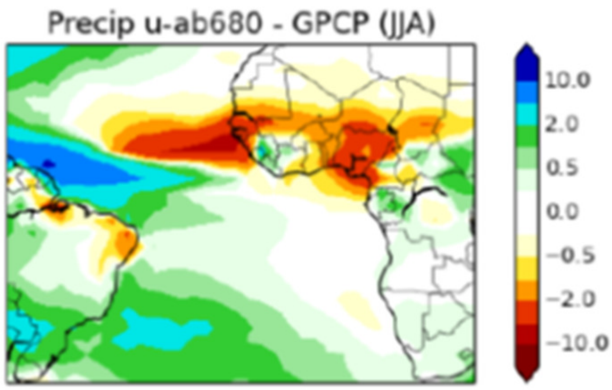

c)

Figure 19: Biases in MetUM JJA precipitation relative to GPCP observations for a) GA6-N96; b) GA7-N96 and c) GA7-N216

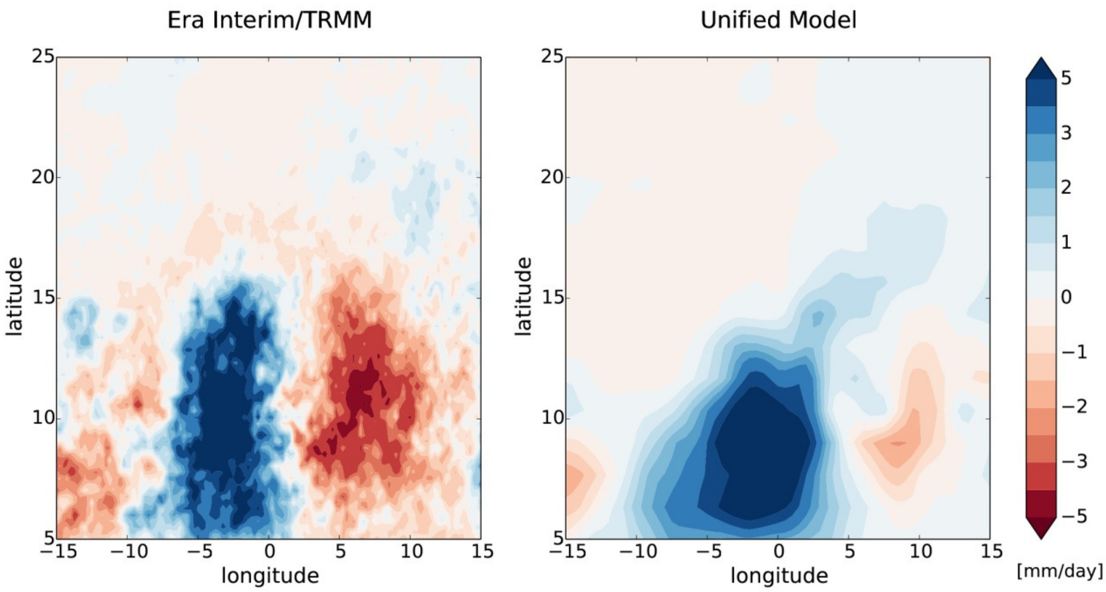

Figure 20: Composites of precipitation for ERA-Interim/TRMM (left panel) and the Unified Model GA7 at N96 resolution (right panel) based on AEW tracking. Only AEW tracks that are in the region 18 to 8 West and 5 to 15 North are considered. Longitude 0 corresponds to the AEW trough location.

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

A new methodology using a Met Office the Perturbed Physics Ensemble (PPE), is being developed to identify the sensitivity of specified climate parameters (e.g. total West African Monsoon rainfall over June-August) to changes in MetUM physics. The methodology is currently being tested on present day climate simulations and will be subsequently be employed to examine the sensitivity of future climate predictions to specific changes to the model physics. The work is being done in conjunction with the investigations on ITCZ sensitivity to hemispheric alebedo (WP1.1a).

The PPE comprises 518 ensembles runs of GA7 generated through perturbing physics parameters associated with model's representation of the following processes: convection, gravity wave drag, boundary layer, cloud and cloud radiation, cloud microphysics, aerosol, and surface processes and snow.

As an example, simulations of WAM June-August rainfall from the "parent" GA7 MetUM and the PPE ensemble are compared with observations in Fig. 21. It may be seen that making changes to the physics can change the rainfall totals substantially. GA7 underestimates rainfall (the dry bias) but the spread in the PPE is sufficient to encompass the observed values.

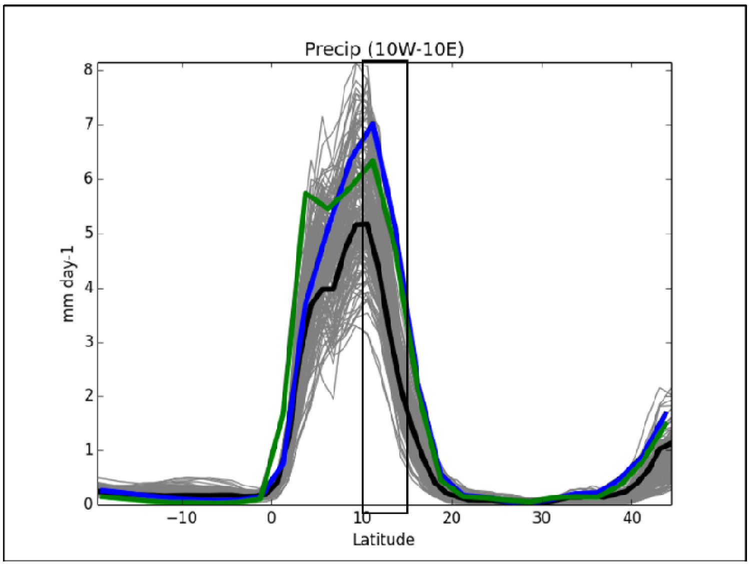

Figure 21: Observed and simulated June-August rainfall associated with the West African Monsoon. Observed rainfall is from GPCP (blue) and CMAP (green). Simulated rainfall is from GA7 (thick black) and 518 members of the GA7 perturbed physics ensemble (grey lines).

It is of key interest to know which physics changes the rainfall most sensitive to, as this will then direct research to the most relevant model processes. A tool referred to as a “statistical emulator” is being used to achieve this. Application of the tool shows that GA7 June-August rainfall totals in the band 10-15N over West Africa (the Sahel) are most sensitive to changes in the convective entrainment rate, as might be expected, but also to cloud radiative effects and cloud lifetime (Fig. 22). Thus the method provides insight to aid further targeted research to improve understanding of these sensitivities – leading to sustainable model improvements.

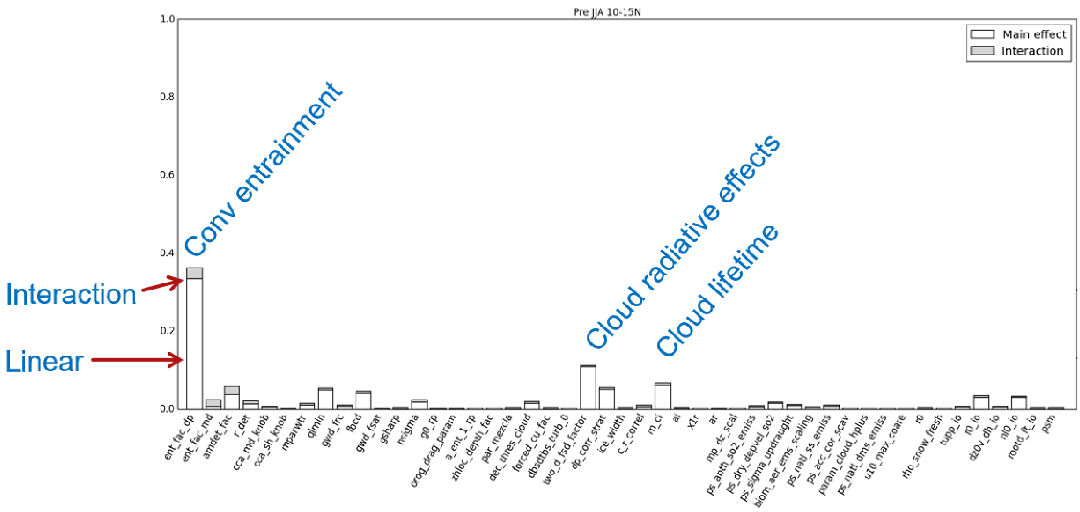

Figure 22: Output from the statistical emulator showing the perturbed physics parameters that GA7 WAM total rainfall (June-August, 10˚N-15˚N; 18˚W-5˚E) is most sensitive to. The clear section of the bars indicates the linear response to the perturbed parameter, the shaded area the response associated with interaction with other perturbed parameters.

Next steps: A coupled PPE using the MetUM (GC3) is currently being produced and will shortly be available for analysis. This will be used to further elucidate the model physical

processes responsible for large scale biases. Implementation in the coupled model framework will assist understanding of processes driving the SST biases in GC2/GC3 referred to for example in work under WP1.1b.

WP4.3 Impact of resolved convection on future projections

In addition to the present-day climate CP4-Africa simulations runs described under WP2, a set of runs simulating future climate, representative of 2100, have now been started. To drive CP4-Africa a 30-year N512 global GA7 timeslice simulation has been run with future RCP85 forcing for the year 2100. Specifically, the climatological difference in sea surface temperatures between a RCP85 (2085-2015), and a historical (1975-2005) HadGEM2-ES simulation has been calculated for each month and added to the observed Reynolds sea surface temperatures. Greenhouse gas concentrations are representative of 2100 under the RCP85 scenario. Aerosol and all other forcing are the same as those used in the baseline simulations.

As with the baseline simulations, the N512 global simulation is being used to provide boundary data to two limited area models: a convection permitting model (CP4-Africa), and a "control" model that is the same resolution and largely the same configuration as the global model but with some land surface parameters changed to match those in convection permitting model (nCP25-Africa). The forcings used in the regional model are the same as those used in the global model but additional consideration has been required to assign the surface temperatures of lakes (as these lakes are not resolved in the global simulation). Lake surface temperature increases have been estimated from near surface land warming in the global simulations, with a small allowance for the inertia of large water bodies.

Next steps:
As CP4-Africa future (idealised) simulations become available work will commence on characterising the impact of resolved convection on future projects on the 5-40 year timescale. A number of initial papers are already planned.

Progress against milestones to June 2018:

Deliverable D4.3a, Spring 2017: Datasets from the present day and future climate runs of CP4-Africa model made available through JASMIN for use by RPCs.

Present day climate simulations from CP4-Africa are available on JASMIN and are being used by FCFA Regional Consortia as reported in Section 4.2. A sample of years from the future scenarios will soon be available. To minimise the delay in delivery (a result of a slower than anticipated turn round on the HPC system) two parallel runs of 5-years each for both present day and future simulations are being processed.

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Appendix 1: Programme for the IMPALA 2nd Science meeting

IMPALA 2nd Science meeting: Progress and plans

19-20 January 2017; *University of Leeds*

January 19th

09.00 – 09.05 Welcome/logistics (Doug/Lawrence)

09.05 – 09.15 IMPALA update and meeting outcomes (Cath Senior)

09.15 - 10.30: CP4-Africa (*Presentations ~15 minutes including questions)*

Overview – Doug Parker

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

Sonja Folwell (CEH) – Surface Hydrology in CP4 simulations

Segolene Berthou (MO) - Extreme Precipitation over West Africa

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

10.30 - 11.00: Tea/Coffee

11.00 - 12.15: Plenary Discussion/BoGS on possible additional CP4 Experiments and links to FCFA RCs (led by Doug Parker and Cath Senior)

12.15 - 13.15: Lunch

13.15 - 15.00: WP2: Improved Representation of local processes (*Presentations ~15 minutes including questions)*

Overview of WP2 – Simon Vosper (MO)

WP2.1 – Convective parameterization development

Overview - Steve Woolnough (Reading)

Michael Whitall/Martin Willett (MO) - Convection scheme developments

Gabriel Rooney (MO) – A new cold pool scheme

Natalie Harvey (Reading) – Development of tools to analyse the TKE budget of an idealised diurnal cycle

WP2.2 – Land Surface Developments

Chris Taylor (CEH) – Land model developments

WP2.3 – Aerosols

Richard Washington (Oxford) for Ian Ashpole (by Skype) – improved aerosol sources

Discussion on WP2 Simon Vosper, Chris Taylor

Progress on deliverables

Plans for year 2

15:00 - 15.30: Tea/Coffee

15.30 - 1700: WP3 Metrics and Model Evaluation (*Presentations ~15 minutes including questions)*

Overview of WP3 – Richard Washington (Oxford) (Skype)

Joseph Mutemi (U of Nairobi) - East Africa (Skype)

Wilfried Pokam (U of Yaounde) - Vertical motion over central Africa (Skype)

Babatunde Abiodun (CSAG, U of Cape Town) - West Africa (Skype)

Ben Lamptey (ACMAD) - West Africa (Skype) - TBC

Rachel James (Oxford/CSAG U of Cape Town) - Evaluation of GC2-N216 over southern Africa, with a focus on Tropical Temperate Troughs (Skype)

Discussion led by Richard Washington to include

Progress on deliverables

Plans for year 3

17.00: End of Day 1

18.30: Conference Dinner (self funded)

January 20th

09.00 - 10.30: WP1: The role of the large scale on Africa (*Presentations ~15 minutes including questions)*

Overview of WP1 – Andy Turner (Reading)

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

Michael Vellinga (MO) - Remote drivers of the East Africa long rains

Linda Hirons (Reading) – Remote and large-scale drivers of variability in the East African Short Rains

Matt Hawcroft (Exeter) – Large scale controls on the ITCZ: hemispheric albedo, energy transports and teleconnections

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

Sean Milton (MO) - Nudging approaches and use of PV tracers (Skype)

Discussion led by Andy Turner to include

Progress on deliverables

Plans for year 3

10.30 - 11.00: Tea/Coffee

11.00 - 12.00: Plenary Discussion/BoGs about WP1 and 2 interactions (led by Andy Turner and Simon Vosper)

12.00 - 13.00: Lunch

13.00 - 14.00: WP4: Integration and Characterisation of model improvements and implications for future climate change (*Presentations ~15 minutes including questions)*

Overview of WP4 – 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

WP4.2 – Characterizing model improvement on key processes for future climate

Matt Hawcroft (Exeter) – The West African Monsoon in HadGEM3 PPE

Simon Tucker (MO) – Progress with Future CP4-Africa experiments

Discussion led by Cath Senior

Progress on deliverables

Plans for year 3

1400 - 1530: Infrastructure, cross project issues, FCFA progress (*Presentations ~15 minutes including questions)*

Infrastructure

Duncan Watson-Parris (Oxford) - JASMIN community Intercomparison Suite

Cath Senior (MO) - Use of IMPALA twiki (5 mins)

Cross Project and FCFA updates

Richard Graham (MO) - FCFA updates including FCFA science meeting in Cape Town September 2017; FCFA Innovation, Mobility and Applied Research Funds

Brief Updates on Pillar 1 work in RCs (Presentations ~5-10 minutes including questions)

Richard Jones (MO) – Update on Pillar 1 work in FRACTAL (Southern Africa) (Skype)

John Marsham (Leeds) – Update on Pillar 1 work in HyCRISTAL (East Africa)

Chris Taylor (CEH) – Update on Pillar 1 work in AMMA-2050 (West Africa)

Neil Hart (Oxford) – Update on Pillar 1 work in UMFULA (Central/Southern Africa)

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

16.00: End of Day 2

Appendix 2: Summary of conclusions of the plenary discussion sessions

CP4-Africa session

1. A problem was discovered by CEH in the soil moisture initialisation during the CP4-Africa experiments after a re-start problem on 1/7/1997. The soil moisture was unexpectedly reconfigured to very wet values ('Biblical flood') across the whole of Africa. Evaporation level 1 soil moisture re-adjust within 1 month but lower level soil moisture are likely affected throughout the run to the point it has reached now (3 years 9 months)
2. The potential for additional CP4-Africa experiments was discussed. These included re-analysis driven experiments to link WP1/2 analysis (this was discussed further in the WP1/2 plenary discussion and will be the subject of detailed planning in the follow up meetings). Other possibilities were to think about runs with revised representation of lakes, or runs with updated physics – maybe at 25km. It was noted that the MO will not be able to accommodate all the runs and so the possibility of running on MONSooN was discussed.
3. There is a need to share common data and analysis tools within IMPALA. We should be using the JASMIN shared space more effectively for any data that has been processed and could be generally useful and also using the twiki pages to share diagnostic analysis and tools. We need all to use Rachel James spreadsheet of diagnostic methods.

Action1: Rachel Stratton to investigate the reasons for the incorrect soil moistures at the re-start point. Does this affect other parts of the run? Will the future runs be affected? Are other variables affected (compare dumps once a new reconfiguration test has been run)

Action 2: Sonja Folwell to upload her current diagnostics analysis to the IMPALA twiki pages to summarize issues. Look at soil moisture on each level and soil properties, LAI. Howe big/long lasting is the problem from a land surface perspective?

Action 3: All CP4-Africa current analysts (Rachel S, Segolene, Declan, Simon Tucker,…) to look at atmospheric response to 'shock' e.g. fluxes, surface energy balance etc. How big/long-lasting is the problem from an atmospheric perspective?

Action 4: Rachel to set-up a third CP4-Africa experiment once we understand the cause (and solution) to the above problem. This 'patch' could run from 1/7/1997 for as long as necessary (or as is possible) given the above analysis. An alternative would be to re-run from start so that other (minor) issues could be corrected and a cleaner overall experiment might result, although given uncertainty over HPC availability in longer run this might be higher risk. Cath/Simon to monitor with Rachel

Action 5: Cath to discuss with Afterburner project (Jamie Kettleborough) the possibility of soil properties being included in automatic monitoring software.

Action 6: Doug and Chris to discuss the possibilities of the using the Biblical flood for research article

Action 7: WP2 (Mike Whitall) to consider using the 25km pan-Africa regional model as a test bed for new physics development

Action 8: Cath to send around an email to encourage CP4-Africa data users to use a group email to share analysis and tool and also to upload information to the IMPALA twiki and log on Rachel James spreadsheet. Some examples might be storm tracking analysis, AEW tracks etc. All users to consider using the JASMIN IMPALA shared workspace for

processed data which might be generally useful (e.g. Segolene has CP4-Africa data re-gridded onto TRMM)

IMPALA WP1-WP2 links session

1. The possibility of running idealised CP4A and nCP25A case studies to examine the local response to QBO, MJO related variability was discussed. These runs would be relatively short, perhaps 2-3 weeks long.

2. The spurious soil moisture forcing in the CP4A present day run (July 1997, the "Biblical Flood" event) may prove useful for understanding the role of strong large scale forcing (i.e v strong El Niño) vs a large continental scale perturbation.

3. We need to understand how well the CP4A N512 global driving model represents the large-scale modes of variability in order to evaluate the local response to teleconnections in CP4A itself. Does the boundary forcing in CP4A respond correctly to large-scale drivers?

4. Testing the local response from new physics (especially convection scheme improvements) is a high priority. This could be done relatively cheaply in nCP25A runs. Each 10-year simulation completes in ~2 weeks.

5. We would also be interested in further global and regionally nudged experiments, both to look at some additional nudging regions and to see the response with physics upgrades (e.g. with GA8 prognostic entrainment). Jose and Sean's recent tests with GA7 suggest that the rainfall error patterns in the tropics do not change significantly when nudging to analysis is applied to wind and temperature. This is consistent with the errors appearing rapidly in short NWP runs. But would this still be the case with new, improved physical parametrizations?

6. There is interest in doing soil moisture sensitivity tests in the nCP25A runs e.g. testing impact of realistic variability in soil moisture vs climatology.

7. It will be important to agree by teleconnections and large-scale forcings i.e. as a group we should agree which are the key ones to focus on (e.g. the "double moisture advection pattern") and coordinate our efforts to look at them. It would also be valuable to coordinate development of diagnostics.

8. We should get Matt Hawcroft's energy flux diagnostics into auto-assess, and also apply them to these runs. ***Does that make sense for uncoupled runs?***

Action 1: Andy and Simon organise a WP1-2 meeting to focus on the aspects of the above. This needs to happen before the Cape Town meeting in September.

Action 2: Not actually a WP1-2 action, but Chris Taylor and Mike Whitall should follow up on discussions about representation of sub-grid distribution of parameterized convective rainfall and its interaction with JULES via the canopy capture/evaporation. We agreed this should happen in 1-2 months, once Mike has made further progress with the scale-aware convection developments.

Doug Parker (University of Leeds) leads the IMPALA WP1-WP2 interaction plenary discussion

Workshop dinner at Jamie's Italian Restaurant, Leeds