Report of the 23rd Met Office Scientific Advisory Committee Meeting (23-25th January 2019)

Response from the Met Office Chief Scientist in red

Summary

The 23th MOSAC meeting was held the 23-25 January 2019. The MOSAC has appreciated that some of the topics covered along the meeting were aligned with MOSAC previous suggestions.

First, MOSAC would like to praise the following staff and organisational highpoints:

i) Obtaining an Athena Swan Bronze Award is a very good step forward in establishing the actions needed to promote diversity and gives confidence in the willingness of the Met Office to promote a strategy to achieve greater diversity in more senior roles. This assuredly will help to attain gender balance within the Principal Fellow team eventually;
ii) The new Principal Fellow roles clearly rewards excellent individuals and support the Met Office strategic needs across Science, except for Data Assimilation;
iii) The creation of the new Research to Operation (R2O) and Operation to Research (O2R) Teams will surely increase the efficiency of the pull-throughs and will insure better co-production of new forecast products by the research and forecast communities;
iv) The new Regional Model Evaluation and Development (RMED) team in Foundation Science is a nice illustration of the Met Office agility to align to the seamless weather-climate goal of the Science Strategy: 2016-2021. As an example, the convective scale numerical environmental and weather prediction model of the UKEP initiative will not only provide robust forecasts of natural hazards a few days ahead it will also provide the downscaling tool for predicting changes in local hazards due to climate change.

We are grateful to MOSAC for their time and efforts at the 23rd MOSAC meeting. We thank the committee for highlighting these four points. We recognise the gap in scientific leadership in data assimilation, which we hope to resolve in 2019. In the following we provide a point by point response to the recommendations and questions raised by MOSAC.

Second, many fundamental aspects of the Science programme were covered along the 3-day MOSAC meeting. The explicit recommendations can be found in the annex Recommendations and Questions.

Predictability and Dynamical/Physical/Chemical Processes

MOSAC was pleased to see the early results of the project ParaCon (Parametrization of Convection) to advance the representation of convection across model scales from 1-100km. The ParaCon results based on the new mass-flux scheme are greatly promising. We encourage the Met Office Science teams to accelerate their engagements with all the ParaCon projects in doing testing and validation to maximise the benefit of this major joint research program with NERC. We recommend to not only look at the tropics in regional and global modelling framework, but also to diagnose the new convection schemes in extra-tropical weather regimes like cold air outbreaks. Especially we encourage the Observation Based Research (OBR) team to engage in the ParaCon project. OBR has a very good record of pull-throughs to model improvements and it should continue embracing ParaCon goals that tackle the most serious gaps in physics understanding and simulation of convection. It is also recommended to see how the new CoMorph scheme behaves in the data assimilation framework as early as possible.

We agree that OBR measurements should contribute to the development and evaluation of the new CoMorph convection scheme and do have some plans. For example, a key focus of the TerraMaris field campaign (early 2020, Indonesia) is the triggering and evolution of tropical convection. We intend to use this experiment as a testbed for CoMorph. It is also clear that one of the major challenges in implementing the scheme will be its interaction with data assimilation in the full NWP system. Following recent investigations (presented at MOSAC) we will be reviewing our NWP testing strategy in order to ensure earlier testing of significant model changes with the data assimilation system.

MOSAC appreciates that the restructuring of OBR this year has created some risks in the way the Met Office operates in terms of the innovation chain: process-based observations, to parameterisation development, to model implementation, to testing and validation and finally to operation. There is a risk that the Met Office will lose leadership and capacity in the first part of this chain. The Met Office will need to watch this closely and facilitate OBR engaging with the wider atmospheric observations community to maintain its influence. OBR needs to identify these key partnerships to maintain the same quality of support to process-based observational research if less can be done “in-house”, including instrument development.

We agree that it will be important to maintain and grow strong partnerships in this area. We intend to continue to work very closely with the Facility for Airborne Atmospheric Measurements (FAAM) and to collaborate with the UK academic community on joint aircraft campaigns. Indeed, the OBR research plans to 2021 currently include three joint aircraft campaigns (UK and international) and we are also engaging with international partners in two joint boundary-layer experiments over this timeframe.

Numerical Weather and Environmental Prediction

MOSAC was pleased to see the major progress made with the implementation of the post-processing system and verification strategy presented at the 20th MOSAC meeting in 2015. The new IMPROVER post-processing system will make its operational products more reliable and effective to develop, especially for ensemble forecasts from high-resolution to planetary scale. It is based on modern open source tools such as Python and NetCDF that will facilitate collaboration. The committee was impressed by the design of the system, its well-ordered processing and stepwise verification, and the fact that it is scalable to run on advanced HPC systems. MOSAC encourages the further development and implementation of "smart" neighbourhood methodologies that are spatially adaptive and account for topography and local features (e.g. urban vs. non-urban, land vs. sea) in order to preserve valuable details. IMPROVER will be an ideal tool for blending inputs with different characteristics, for example nowcasts and NWP, convection permitting and convection parameterising models, but use of the outputs in operational forecasting remains a challenge.

We are grateful to MOSAC for supporting the overall approach adopted in IMPROVER. The development and implementation of the IMPROVER post-processing system is a priority for the Science, Technology and Operations directorates of the Met Office. Improvements e.g. interpolations near sloping topography, are underway, but will accelerate once the initial capability is implemented by March 2020.

For the global NWP perspective, traditional sub-grid scale parameterization of convection and gravity wave drag are entering a "grey zone". This will need to establish a solid research plan that will address the representation of physical processes.

We agree that this is an important challenge, and it is likely to feature strongly in our new science strategy. The Met Office has made some progress in this area in recent years, with the introduction of an initial scale-aware "blended" boundary layer scheme in convection-permitting formulations of the UM (including UKV and MOGREPS-UK); playing a leading role in GASS grey zone cold-air outbreak inter-comparisons (Field *et al*., 2017), the follow-on GASS (sub)tropical inter-comparisons (Tomassini *et al*., 2018), and leading work on the grey zone behaviour of gravity-wave drag parametrizations (Vosper *et al*., 2016). We are also running global climate simulations at grey zone resolutions (PRIMAVERA) and engaging with the international community in the EUREC4A project.

The Next Generation Modelling Systems (NGMS) programme does not seem to have taken the data assimilation specific needs into full consideration, more specifically large and higher frequency Input Output (IO) processes and big memory needs. The future Data Assimilation software framework needs to be considered earlier on.

We agree that data assimilation (DA) needs to be considered early, and recognise that progress is not as advanced as work on the dynamical solver. Over the past 12 months, the NGMS programme has including a scoping project to review requirements and possible solutions for next-generation observation pre-processing and DA. Current efforts are focussed on assessing the suitability of the Joint Environment for Data assimilation Infrastructure (JEDI), including the significant technical challenges associated with the development of efficient, portable, cycling, coupled DA schemes with the huge volumes of observations and large ensemble sizes anticipated in coming decades.

In addition, as reported to MOSAC, we are now recruiting a manager for a new "data workflow group" who will initiate a project to explore exactly some of these software engineering aspects.

For the regional NWP perspective, the RMED group working on regional models addresses a clear need for Weather and Climate sciences. Regional scale at least to UK region should consider going to more sub-km scale, both of in terms of model physics, Large Eddy Simulation (LES) and turbulence, and the methods and data needs for initializing sub-km scale forecasting will demand new research efforts. The development of the new strategy should provide an incentive for the Met Office to revisit its previous probing of sub-km forecasts, that seemed to indicate, at the time, that only weak benefits seem reachable. MOSAC would appreciate having a better understanding of the R&D plans to tackle these future challenges.

We agree that previous efforts to explore sub-km resolution modelling have demonstrated only marginal benefits in terms of the behaviour of convective precipitation but, for other aspects, such as near-surface temperatures and fog, the benefits are quite significant – particularly in complex terrain or areas with highly heterogeneous land surface. We also agree that this is an important area of fundamental research and is likely to feature strongly in the new science strategy. We will be happy to provide further information about our plans in this area at a future MOSAC meeting.

MOSAC is worried that the new model GungHo and the supercomputer software infrastructure LFric project, with its tight delivery schedule and under-resourced workforce, will not pay attention enough to the flexibility needed for the coupling and modular aspects of Environmental and Earth-system Prediction research. The fulfilment of these requirements is critical for the future activities of Atmospheric Dispersion and Air Quality (ADAQ), Ocean Forecasting Research and Development (OFRD), UK Environmental Prediction (UKEP) and for healthy university collaborations and global partnerships. The future of numerical weather, climate and environmental prediction will thrive in a more complex landscape. In face of this complexity the R&D agenda needs more numerical experiment flexibility than what is available now in the UM.

We have crystalized the design requirements for the new LFRic system, and greater flexibility and better usability features highly. But we do agree that this could become a lower priority while the Next Generation Modelling Systems (NGMS) programme is under-resourced and working towards challenging timescales. We are considering how we can increase external collaboration across the NGMS programme (this would be particularly welcome from UM Partners) and exploring whether there may be opportunities in this area. Furthermore, we are actively re-examining the resourcing of the NGMS programme, and would be happy to report progress to MOSAC at a future meeting.

Data Assimilation and Observations Research

MOSAC notes the significant increase of NWP skill associated with recent DA pull-throughs which, in a way, demonstrates the great quality of the underlying NWP Unified Model (UM) system.

MOSAC would like to have a better understanding of the actual and contingency plans for DA development, with regards to the use of all-sky radiance, and the development of DA for LFRic, the coupled and holistic DA development from regional to global prediction, from weather to climate, from atmospheric to coupled environmental sub-systems, and the dependency on international collaboration. For the latter MOSAC would like to be kept informed on the outcomes of the audit of the JEDI/Met Office collaboration that will be performed in the next few months.

Plans for short-term (1-3 year, UM-based) developments in DA (e.g. coupled NWP, all-sky radiances – first implemented in PS41) and longer-term (post-UM) DA strategy were presented at MOSAC in 2017. Enhanced collaborations with international partners (e.g. JCSDA, NCAR, ECMWF and UM partners), maintaining expertise/resource in key areas, and the use of open-source DA software where possible, are all important aspects of our DA strategy, intended to reduce risks to the delivery of world-leading DA capabilities for NGMS by 2024-5. We look forward to providing a further update at a future MOSAC, including our findings from the detailed assessment of the NGMS-JEDI DA interface.

Probabilistic Forecasting

Ensemble forecasting is increasingly omnipresent in all forecast applications at all time ranges and all spatial scales. MOSAC finds that it is an area where there is actually very little “seamlessness” between timescales. This needs to be better understood. The Met Office human resources and supercomputing infrastructure are limited in view of developing ensemble prediction systems. MOSAC encourages the Met Office to develop more collaborative activities (especially with ECMWF) and comparison experiments with other similar operational ensemble prediction systems.

We agree that Met Office uses different methods to develop ensembles across the weather and climate timescales. Consideration of these approaches is likely to be a strong element of the next science strategy.

As presented at MOSAC, WMO CBS results indicate competitive performance in terms of CRPS of the MOGREPS-G ensemble, which will be further enhanced in 2019 with the implementation of a new En4DEnVar initial condition perturbation update mechanism and upgraded inflation scheme. Recent enhancements (e.g. SPPT) have benefitted from collaboration with ECMWF (and other) scientists, but we acknowledge that further joint activities would be worthwhile so we commit to pursuing a joint predictability workshop in 2019.

Weather-related Hazards and Impacts: Operational and Customized Forecasts

MOSAC notes the important role of the O2R team (expert meteorologists) in diagnosing problems with the model that require urgent attention and encourages the model development teams to prioritise work in those areas that are causing the Met Office's operational forecast services to be less accurate. MOSAC saw that there was great value in having the forecasters provide guidance to the researchers. Another way to do this is using test beds, as seems to be the case at the Met Office. The Committee maintains that the O2R testbeds keep researcher involved with the forecasters. This seems to be successful in the U.S.A. in the aviation and severe weather areas supported by NOAA.

MOSAC is pleased to see that Applied Science and Business Group science is thriving. The staff is now over one hundred full time employees, indicating a rapid growth rate since its creation five years ago. It has reached out to various users through a risk-based framework. The rapid growth rate brings challenges in how well Applied Science staff are integrated into the programme. Applied Science could take more advantage of ongoing observational and foundational programmes at the Met Office. For instance, the aircraft icing work could benefit from data collected by the cold air outbreak field program (supercooled liquid water), as well as the microphysical parameterization development work in Foundation Science.

We thank MOSAC for these positive comments. We note that, whilst the combined staff in Applied Science and Business Group now number over 100 people, it is fewer than that in terms of Full Time Equivalents (FTEs). The growth in FTE has been about 10% over the 5-year period. Growth has been careful.

In previous MOSAC meetings we have described how Applied scientists have taken advantage of research in other areas of the Met Office Science Programme, for example new Observations instrumentation have been deployed to tackle Heathrow fog issues, and sub-km ultra high resolution modelling has been developed in conjunction with Foundation Science. Nevertheless, we recognise the importance of staff in Applied Science and Business Group being fully integrated into the Science Programme, and we shall endeavour to highlight this point in future papers submitted to MOSAC.

MOSAC's suggestion of using data from e.g. cold air outbreak studies is very helpful. We will explore opportunities for greater use of our airborne and ground-based research measurements in Applied Science.

Climate Research

An underpinning aspect of the Climate Science programme is the development of climate models in a seamless manner with Weather Science and Foundation Science programmes. This seamless framework is certainly advantageous in many aspects. As an example, there have been demonstrated promises in using ensemble and data assimilation techniques for estimating and quantifying the physical parameters and systematic biases in climate models. Along the same line of thoughts MOSAC has well received that the reliability of attribution work was looked at in the context of seasonal forecasts.

MOSAC notes the large climate sensitivity of the latest model is accompanied with a cold bias in 20th Century temperatures. This would need a more in depth understanding of the underlying mechanism responsible for the bias relatively to the increased sensitivity. As an example, in the seamless prediction framework it would be desirable to test whether the interactive aerosol schemes responsible for large climate sensitivity in the climate models, do not produce significant biased increments when the model is run in data assimilation mode and compared with observations.

The climate sensitivity of the new global climate model is something we are very actively investigating. We thank MOSAC for this suggestion, and intend to explore this idea by attempting some well-designed NWP experiments to explore the sensitivity to the GA7 aerosol and cloud scheme changes. To do so will require careful consideration of how the aerosol interacts with the DA scheme.

Overall, MOSAC considered the Hadley Centre as one of the world's leading climate centres.

Toward the next Science Strategy

MOSAC is looking forward to helping the Met Office to develop its next Science strategy and review its implementation in the years to come. The initial thoughts on the future strategy presented by the Met Office Chief Scientist, Prof. Stephen Belcher, are:

- A unified modelling system – open to all
- Ready to resolve: the path to high resolution
- Fusing simulation and data sciences

These bring the following reflections.

- A unified modelling system – open to all

The unified modelling system approach is clearly the key to success for many national meteorological services. The skill of global numerical weather predictions will continue to improve significantly. This will be accompanied by significant improvements in global quantitative precipitation estimation and forecasting thanks to convection-allowing models and data assimilation advances. As the skill of these systems increases over the coming decade, more and more components of the Earth-system will need to be considered to maintain progress (e.g. ocean and sea-ice). We are approaching a new era of environmental prediction where these geophysical sub-systems coupled to the atmosphere need to be better simulated not only to advance weather prediction but also to provide new forecast variables (e.g. river flow; sea-ice extent) with undeniable socio-economic benefits. This will need enhanced and better-quality university collaborations and global partnerships, hence the importance of "open to all". This will be only possible if the UM and LFric are amenable for collaboration.

We thank MOSAC for these suggestions and look forward to discussing our future plans with MOSAC. As noted above, usability is a key design requirement for LFRic. As the new model nears the point where it is ready for wider use we will need to carefully consider issues around portability and ease of access.

- Ready to resolve: the path to high resolution

The increase of supercomputing capability will permit the creation of multiscale models and data assimilation systems with realistic coupling to chemical, hydrological, and surface processes. The comprehensive calculations performed with very-high-resolution models on massively parallel supercomputer will require extensive development of new numerical techniques that NGMS team are developing. Various innovative methods in NWP are developed in Science to address the numerical stability, accuracy, computational speed and flexibility required to handle a larger number of prognostic variables, and the interaction between resolved and unresolved dynamic and physical processes. In the future, exascale supercomputer systems used by Met Office interdisciplinary teams must be capable of routinely handling many petabytes of data and attaining peak performance of tens of petaflops.

This will no doubt entail significant changes to hardware and code design that will affect users and partners. Some of these Science challenges are discussed in more details in the Annex Recommendations and Questions.

We agree with MOSAC that weather and climate models require substantial re-design in order to meet these challenges. Detailed responses are provided to the questions in the Annexes below.

- Fusing simulation and data sciences

Global and regional numerical weather environmental-coupled prediction systems will become ubiquitous and will be the cornerstone of automated decision-making. The future will see more emphasis on further automation of the forecasting process, allowing for more effective manual intervention in critical weather and environmental situations and improved techniques for forecasting the impacts of weather-related hazards. The information from these forecasts will feed applications tailored to the needs of end users. Considering the complexity and the huge size of the dataset generated by next generation NWP systems, it is evident that artificial intelligence (e.g. deep learning) and machine learning techniques will be used routinely to integrate forecasts into the decision-making process. This will need more and more R2O and O2R processes being integrated in the innovation chain at the Met Office. The creation of the R2O and O2R teams is a good step toward that objective.

We will provide in the Annex Recommendations and Questions ideas aligned with these three themes. MOSAC hopes this will help the Met Office to strengthen and grow its scientific and technical excellence for the benefits of UK and its UM partners.

We are grateful to MOSAC for their support in Met Office pursuing the use of Data Sciences to complement simulations. We would like to report progress at a future meeting.

Concluding Remarks

MOSAC would like to thank the speakers and poster presenters for their efforts and readiness to discuss all aspects of their work. Lastly, we would also like to provide many thanks to the Met Office leadership and the administrative staff for this interesting, fruitful and well-organized meeting.

Gilbert Brunet (Chair) on behalf of the Met Office Scientific Advisory Committee (Janet Barlow, George Craig, Elizabeth Ebert, Alain Joly, Erland Källén, Tim Palmer, Ian Renfrew, Roy Rasmussen and Fuqing Zhang)

Annex: Recommendations and Questions

Foundation Science

Foundation Science carries out research underpinning improvements in the Met Office modelling capability for weather and climate prediction. These comments will focus on the NWP aspects of the work. Foundation research is a historical strength of the Met Office, which has an almost unique capability among national meteorological services to address fundamental questions relating to atmospheric modelling and aspects of Earth-system modelling. The success of this work over many years is reflected again this year in the outstanding record of scientific publications and in the NWP scores (second only to ECMWF). The reports and presentations to MOSAC document the achievements over the past year and shows the priorities that have been identified to maintain this record in the context of resource constraints. A prerequisite is to enable communication and collaboration across the Met Office, a large and diverse organisation, and with a large network of external partners.

The Foundation Science Directorate has shown a good awareness of the coming challenges in model development, including new computer architectures, "grey zone" issues for parameterizations, and machine learning, and have (very!) ambitious plans to address them. The ParaCon project is an excellent example of fundamental research, rethinking the basis of cumulus parameterization, but in a way that will address the central problems of the current model. The approach to machine learning is sensible, focusing on “low-hanging fruit”, particularly use of neural networks to improve efficiency of parameterizations.

FS-R1**:** The above strategy should be revisited regularly given the rapid evolution of the machine learning research field.

We wholeheartedly agree with this comment and will re-assess our approach as we learn more from our own research (e.g. from results of emulating the radiation scheme) and in light of the rapidly expanding efforts in the atmospheric science community.

The directorate features six strategic areas, working on observations, dynamical and physical processes, global and regional models, and finally science partnerships. The overall modelling strategy, especially regarding the global model, has been a major contributor to achieving the milestones of the business plan for the current supercomputer. Developments in the dynamical core show a longer-term strategy bearing fruit, with ENDGame succeeded by GungHo in a well-planned development cycle. The future of the modelling infrastructure and capability to respond to future developments in computer architecture is addressed by the LFRic framework.

FS-R2**:** This project is future oriented and very ambitious but may be significantly constrained by limited human resources. If the plans turn out to be overreach, then further development of alternative strategies (Plan B) will be essential.

We recognise the need to direct additional resource to the NGMS programme over the coming years and are exploring opportunities to fund this work and to recruit the right staff. We will also need (and intend to) resource Plan B (i.e. continued optimisation of the UM) in order to fulfil the needs of UM-based climate modelling for CMIP7. We shall keep MOSAC informed of developments at future meetings.

The communication and cooperation between different areas within Foundation Science seems effective, including between observation scientists and model developers. Process Evaluation Groups (PEGs) are effective mechanism, and the recent improvements in gravity wave drag parameterization are an example both of cooperation within the Met Office and exploitation of cooperation with WGNE and ECMWF. On the other hand, the difficulties in implementing the latest global model into the NWP system show a need for taking a more holistic approach to testing, and the plans under discussion for a testing framework that includes data assimilation would be an appropriate way to address this problem.

As NWP systems become more complex, testing strategies also become more complex – something other NMS are grappling with. We plan to review our testing strategy and implement an approach that includes data assimilation trials at an earlier stage in the process. The new approach has already been initiated for the final changes being included in the next global model science configuration (GA8). This is a subject that we shall need to keep under constant review, and shall need to consider what we can learn from other centres.

FS-R3: The development of the stochastic physics might benefit from a similar approach.

Our future strategy is to represent uncertainty where it exists within the physical parametrizations. Collaborative research in this area, including with ECMWF, would be welcomed.

The new RMED group addresses a clear need, and has shown some early successes, for example in reducing screen temperature biases over the UK. Unifying the UK and tropical versions of the model is an important goal.

FS-R4: It will be important to develop a medium-term strategy for this area that will strike a balance among problems arising from NWP, regional climate, and air quality applications.

We would be happy to present a further update on regional modelling progress and plans at the next MOSAC meeting. This will include plans for sub-kilometre modelling as well as coupled regional prediction.

Science Partnerships have been very successful in linking with academic researchers in the UK, and collaborations with international partners are being increasingly developed. These collaborations are poised to play an increasing role in the development of Met Office systems and may include critical dependencies in future (e.g. data assimilation in JEDI). This will pose new challenges for managing risks in these programs. Overall Foundation Science maintained an outstanding programme of fundamental research, preparing for long-range (5-10 year) developments in weather and climate prediction. The Observation Based Research (OBR) area will be discussed below.

We thank MOSAC for their supportive comments and appreciate their expert advice on the Foundation Science programme.

Weather Science

MOSAC's overall impression is that the UKV and fine-scale limited area systems are at the forefront, which is a change with respect to previous years, when the global system appeared to dominate. There were many examples of this throughout the meeting, those related to Weather Science are summarized below, but the creation of the RMED group within Foundation also exemplifies this.

A notable example is the near implementation of the last development promised in the business case that enabled the Met Office to obtain the current HPC. This is the impressive upgrade of the MOGREPS-UK system (3 members per hour up to +120h). It will be challenging to use it properly, especially as the new IMPROVER post-processing, specifically designed to handle all this information, is not ready. It will also be challenging for the forecasters. Noting that a proper way to use ensemble forecasts to make difficult warning decisions remains a rather open question, with scientific aspects, some of them probably social science questions (e.g. decision making under stress). Another reason to follow this has to do with the assessment of the Met Office achievements with that investment: if it is focused on the socio-economic benefits, then the optimal utilisation of the data is a very important outcome in view of measuring success.

WS-R1: MOSAC would like to be kept informed of the above aspects.

We would welcome the opportunity to discuss further these points with MOSAC. The IMPROVER post-processing system will be implemented in 'beta-testing' mode in early 2020, thus allowing Science and Operations to begin to exploit the new hourly-cycling MOGREPS-UK less than 12 months after its implementation. Forecasters do already have access to the output via web-pages, and are actively engaged in the assessment of future upgrades.

MOSAC appreciate the very remarkable new opportunities and directions relating to fine scale data assimilation: the direct use of radar reflectivity, the Mode-S aircraft data, the work starting in order to introduce a flow dependent component into the hourly 4DVar using (as much as possible) the existing MOGREPS-UK, the implementation of marine forecasts at the same resolution as the deterministic UKV.

WS-R2: However, MOSAC would like to hear more about land surface data assimilation, especially in the limited area systems.

Current land-surface data assimilation efforts are focussed on a) Implementation in UKV, and b) Assessment of the NASA/LIS system to replace the in-house 'SURF' system. We would be happy to provide an update at the 24th MOSAC.

For the Data Assimilation perspective, the global forecasting system will benefit from the rain affected radiances, the AEOLUS wind (based, however, on level 2 data from ECMWF for a start). At the end of 2019, the long-term investment of the Met Office into the EnVar approach will have a first operational implementation, in the form of an ensemble of 4DEnVar. It will improve the initialization of MOGREPS-G.

WS-R3: The Met Office is encouraged to perform a cost/benefit analysis of extending to the Tropics the abovementioned improvements to the convective-scale DA as well as the use of an En-4DEnVar and implementing them in the regional version of the UM.

We welcome this recommendation. Following the successful implementation of tropical, convective-scale DA in the 'SINGV' project, we are exploring further applications in SE Asia through Newton Funded projects. A successful UM partner workshop (~40 attendees) was held in Wellington, New Zealand in March 2019 to explore expanded collaborations in high-resolution ensemble/variational DA and radar reflectivity in 4DVar. A convective-scale En4DEnVar is a natural extension to the hybrid 4DVar/4DEnVar project currently presented as a poster at MOSAC.

Most remarkable is the development of IMPROVER, covered in another paper, as well as the work on verification. In-depth work is going on to prepare Stable Equitable Error in Probability Space (SEEPS) score on precipitation forecast (score advocated by ECMWF) or to gain in-depth understanding of the fractional skill score for future use. It is interesting to note that the HIRA score, that sets MOGREPS-UK as a better source of information than the UKV, is the one presented to MOSAC, yet it does not become a Key Performance Indicator (somewhat deviating from the initial point of putting fine-scale systems in the forefront).

WS-Q1: *What prevents HIRA to replace the current UKV performance indicator? Is it a technical issue? Is this related to the difficulty for forecasters to move towards ensemble-forecast based work?*

This is a complex question because performance metrics serve two purposes in the Met Office: a) To measure the quality of Met Office products in ways that sponsors value and b) To inform and guide Met Office Science research priorities which ultimately lead to future products. The continued use of a deterministic PWS UKV performance indicator is driven by the predominantly deterministic nature of current public forecasts. We anticipate that the transition to ensemble-based metrics will happen over the next few years as IMPROVER (with ensembles at its core) is implemented, using the verification science developed in HiRA (and presented at MOSAC). In order provide continuity in Met Office corporate KPIs, we have agreed to wait until IMPROVER is implemented before reinstating a KPI measuring UK NWP.

WS-R4: MOSAC would be interested in a discussion on the balance of effort between NWP system development and post-processing.

This is a subject of very active discussion within the Met Office, and we would also welcome a discussion on this topic with MOSAC.

Ocean forecasting research is also an area where exciting projects are moving forward. This group is also involved in the NGMS programme. One direction worth mentioning is the development of ocean ensembles.

WS-R5: Now, given the limited resources in this area, MOSAC is interested to see how in the future the partnership (and investment) in Mercator Ocean provides mutual help for both institutions moving forward into their strategic objectives.

The expanded Mercator collaboration builds on our already significant European ocean activity supported by the Copernicus Marine and Environmental Modelling Service (CMEMS). We would be happy to provide an update at a future MOSAC.

In the area of air quality, a nuclear accident dispersion model has been developed cooperatively. MOSAC is pleased to learn that the Met Office will make decisions as to the future of its several atmospheric dispersion codes to avoid duplication of efforts. MOSAC recognise the resource constraints affecting ADAQ group activities, and the decision around potential use of offline model NAME for air quality forecasting vs. AQUM. We look forward to clarity on this next year and an update on any relevant work enabled under the Strategic Priorities Fund (SPF) Clean Air Project. With the emphasis on ensuring next-generation post-UM systems, there should be a consistent long-term strategy for coupled chemistry-atmosphere model development, especially for urban regions.

WS-R6: MOSAC would like to be kept informed of ADAQ future plans.

Ongoing work to assess the suitability of NAME for AQ applications will be summarized in a key deliverable report in December 2019. We would be delighted to present these and future plans at the 24th MOSAC meeting.

Climate Science

An underpinning aspect of this programme is the development of climate models. This feeds into work on global climate sensitivity and feedbacks, on regional climate dynamics, on climate attribution and on impacts. The issue of how to translate the research into actionable deliverables which can be fed to operational climate services is an important aspect of the Hadley Centre's work. The structure of the Hadley Centre was briefly reviewed, including the appointment of new Senior Research Fellows.

A number of highlights of recent work of the Hadley Centre have been presented. The first was the UKCP18 probabilistic projections, co-designed and developed with users. It was claimed that this was now able to answer questions about extremes, about plausible sets of realistic future weather, of sea-level rise around the UK coastline and whether Paris agreement targets would be met. A second highlight was the contribution to CMIP6 where the HadGEM3 physical coupled model was indicating an equilibrium climate sensitivity of nearly 6K. An Earth-System version of this model had a somewhat lower climate sensitivity but indicated some interesting new interactions between carbon and nitrogen cycles. A third highlight was research indicating high seasonal predictability of summer rain over Northern Europe. Another important highlight was the work on event attribution (e.g. of the summer 2018 heatwave over the UK).

Of course, there remain considerable uncertainties in climate predictions and projections as well as in climate sensitivity and impact attributions, particularly at the regional scales and for extreme events, and a difficult question for the Hadley Centre is how to balance the need to emphasise that modelling the climate system is not a “done deal” with the need to promote some of the latest model outputs from the Hadley Centre. This is put into sharp focus since the large climate sensitivity of the latest model comes at the price of a cold bias in 20th Century temperatures.

CS-Q1: To what extent does the latter undermine the credibility of the former? Moreover, to what extent and how uncertain will the projected global warming impact the regional climate for the UK, and can such uncertainty be sufficiently quantifiable to assess climate risk at the regional scales?

These questions will be actively investigated for some time, and there are early indications that other international modelling centres are seeing similar results from their new generation models. The performance of the model for the 20th century remains an area of active work that we would be happy to present to a future MOSAC meeting.

As part of the UKCP18 development we assessed improvements in simulation of the UK climate, including dynamical aspects such as the position and activity of the storm tracks. The UKCP18 product included simulations from the new model, complemented by simulations from the CMIP5 models. In this way a broad range of climate sensitivities were sampled in UKCP18 output.

It was encouraging to see that the reliability of attribution work was being measured by studying the extent to which the specific climate extremes being attributed could be reliably predicted e.g. in seasonal forecast mode.

CS-R1: This work should be continued until it has matured into a state where it can be applied routinely to new extremes as they occur.

We thank MOSAC for this recommendation. We intend to continue this work. We will provide more details on the link between event attribution and seasonal forecasting next year.

Overall, the Hadley Centre’s research is of enough quality to maintain its position as one of the world’s leading climate centres, and publications and citations continue to be outstanding. However, the Centre faces challenges – not least in the modelling area where resolution, ensemble size and Earth-System complexity all vie for valuable computer resources, and where developments will need all the human resources that are available. Regarding the former, every effort should be made to ensure that processes are not represented with more precision than is justified theoretically. Conceivably, AI can play an important role in representing complexity in simplified form. Meanwhile, there have been demonstrated promises in using ensemble and data assimilation techniques for estimating and quantifying the physical parameters and systematic biases in climate models.

CS-R2: MOSAC suggests that it will be critical to engage in collaborative partnerships to push these areas forward.

We agree that the challenges posed by climate change demand a well-planned scientific effort that balances computer and human resources, and that structured partnerships will be crucial. In particular we anticipate that data sciences will form an important new element of the next science strategy. We look forward to reviewing these points at future MOSAC meetings.

Regarding the large climate sensitivity, the Met Office has been at the forefront in developing seamless prediction systems. In principle, therefore, it should be possible to test whether the interactive aerosol schemes which are in part at least responsible for large climate sensitivity in the model, do not produce biased increments when the model is run in data assimilation mode and compared with observations. However, it is understood that the model is not currently "seamless" as far as such aerosol schemes are concerned.

CS-R3: MOSAC thinks it is a matter of some urgency, not least regarding the reputation of the Office as a leading scientific organisation, to ensure that the new interactive aerosol schemes used in the climate model are not producing enhanced temperature biases in very short-range weather forecasts.

We agree that the seamless approach pioneered at the Met Office provides scientific opportunities for investigating aerosol processes: See comment above regarding NWP tests.

<u>Applied Science</u>

Applied Science is now 5 years old and thriving. MOSAC considers this a great success story and a model to inspire other National Meteorological and Hydrological Services. The staff is over 100, indicating a significant growth rate. It has reached out to various users through a risk-based framework. The focus on risk seems to have been successful in connecting to users and building the programme. However, MOSAC would like to propose a few recommendations that could help Applied Science to continue its growth:

Please see comments above on staff numbers and growth rate in Applied and BG Science.

AS-R1: There are other areas that users can relate to including education and decision support systems. These may be considered as additional paths to user engagement.

We thank MOSAC for this recommendation.

AS-R2: A unique challenge for Applied Science is programme development. This is an additional overhead that is often not funded well. MOSAC suggests that the Met Office consider providing a higher overhead return rate to Applied Science for this purpose.

We agree that there is an important challenge in getting the right balance between development and chargeable work. Met Office is subject to government rules on contracts and charging, which means that for the majority of our contracts the overhead rates (etc.) are not negotiable. At a future MOSAC we would be happy to discuss further examples of how Applied Science has both used and inspired fundamental scientific work.

AS-R3: Ensure that the staff is sufficiently connected to relevant academic research in their area. To address this challenge, MOSAC suggests that Applied Sciences take advantage of student placement schemes, masters, PhD projects, etc.

We are grateful for this suggestion. Applied Science is actively involved in Met Office student placements and regularly takes on two or three a year. In addition, several of the Applied Science staff are undertaking a PhD course. We are also currently investigating other mechanisms for staff training and for academic collaboration.

AS-R4: MOSAC thinks that staff should have enough training and opportunity to engage with other relevant groups in the Met Office to ensure deeper understanding of models and observational capability.

MOSAC identify an important issue here, namely how to ensure that Applied Science staff remain at the cutting edge. Firstly, the majority of staff are recruited from other Science and Operational areas within the Office. We see this as an important way of transferring up to date knowledge into this area. Secondly, Applied and BG-Science staff engage with other Science areas (e.g. seasonal forecasting) when specialist customer requests require it.

While it is exciting to be in a rapidly growing organization, it also comes with challenging questions for Applied Science:

Please note the comment above that FTE effort in Applied Science and Business Group Science has grown modestly by only 10% in the last 5 years.

AS-Q1: Are there enough skilled staff to do the project management, science, software engineering and meet deliverables?

Where appropriate, project management is done through trained project managers (rather than the scientists). Acquiring specialist skills is a challenge for the whole Met Office Science Programme, particularly of software engineers. We are investigating different ways of addressing these issues and would be happy to discuss with MOSAC at a future meeting.

AS-Q2: Are they agile enough to rapidly hire staff with the appropriate skill sets to meet the project demands?

Establishing process for managing and deploying staff time was an important aspect of setting up Applied Science. Because Applied Science sits within a larger Science programme, when needed and available, staff can be temporarily redeployed from other areas of the Science Programme. More than 95% of Applied Science projects deliver on time and in full, which provides some evidence to this question.

AS-Q3: Is scientific quality maintained due to the heavy workload? Is the rate of publication of journal papers increasing as more staff are hired or are staff too busy with project deliverables to publish?

The priority and focus in Applied Science is delivering to customer requirements. Scientific quality and integrity is maintained through a Met Office Science-wide policy of formal review of the scientific approach, coding, documentation and reporting. Against this background, a proud achievement of Applied Science has been its growth in peer-reviewed publications over the past 5 years:

2013 – 18 papers
2014 – 24 papers
2015 – 30 papers
2016 – 31 papers
2017 – 57 papers
2018 – 49 papers

AS-R5: MOSAC suggests providing additional information on Applied Science at the next MOSAC meeting through additional talks and posters.

We would be happy to report more fully on the scientific work of Applied Science at future MOSAC meetings. We do note, however, that some of the work is commercial in confidence.

Operational Perspectives

The speaker and annex indicated that there was great value in having the forecasters provide guidance to the researchers. MOSAC notes that there is a lot to be gained by forecasters giving regular briefings to researchers on forecast challenges regarding either specific cases or general behaviours. This makes researchers aware of explicit problem areas that may require additional analysis. Another way to provide forecaster input to researchers is by using test beds in which the forecaster and researcher are both present like it is already done at the Met Office. As an example, NOAA Test Bed on Aviation seems to be work well in the U.S. forecasting environment.

OP-R1: MOSAC suggests that part of this O2R effort entail training to help forecasters become more familiar with ensembles in order to enhance the scientific exchange and improve their forecasts.

We agree, and hope to expand the interactions with the advent of the new hourly-cycling MOGREPS-UK system.

OP-R2: MOSAC suggests that the Met Office consider developing a High-impact Weather Test Bed.

We thank MOSAC for this suggestion and will investigate. Met Office Science and Operational Forecasters have experience in several testbeds, including a real-time NOAA/Oklahoma US HWT, and real-time tropical pacific, convective-scale test bed. Active engagement of forecasters in the parallel suite process, and scientists in the day-to-day evaluation of operational NWP, also ensures a semi-continuous UK testbed environment.

OP-R3: It was noted by the presenter that the forecasters often focused on case studies rather than overall statistics of performance. MOSAC suggests that it would be good if there was a better balance between the two.

We thank MOSAC for this suggestion.

Probabilistic Forecasting

An overview of developments of the MOGREPS system was presented. To start the various scoring metrics were described, including spread-skill, CRPS, Brier Score, ROC, Potential Economic Value and Summary Scorecards. Time series of CRPS intercomparisons with other operational centres were shown – indicating that much (but certainly not all) of the differences come from the different underlying deterministic models. Recent improvements in spread associated with the new PS41 system were shown. Some negative impacts on CRPS were found in T850. However, these could not be attributed to the ensemble itself, but were instead associated with changes in the deterministic model.

The PS43 upgrade was described. The most important change was the replacement of the Ensemble Transform Kalman Filter with an ensemble of 4Dvar assimilations. The development of Stochastic Physics was also described. This included the continued use of the stochastic backscatter scheme, the use of a variation of the ECMWF SPPT scheme, and an “Additive Inflation” scheme where a random analysis increment is added to the model fields at each timestep. The use of stochastic parameter perturbations was dropped. The positive impacts of these additions were shown and it is planned to implement the PS43 scheme late in 2019.

Although there are commonalities, the Met Office ensemble system differs significantly from the ECMWF system (the former uses neither singular vectors nor stochastic parameter perturbations whilst the latter does not use stochastic backscatter). In principle one would like to understand the reasons for these differences and to what extent different choices can be justified physically. On top of this, human resources for developing MOGREPS are limited.

PF-R1: As such, this may be an area where more active collaboration between the Met Office and ECMWF can be justified.

Our future strategy is to represent uncertainty where it exists within the physical parametrizations. Collaborative research in this area would be welcomed.

Ensemble forecasting is an increasingly important area, which affects all time ranges and all scales, from very short-range forecasting to long-term climate prediction. This is an area where there is actually very little “seamlessness” between timescales. The limited area model ensembles do not use stochastic physics representations, except for a random parameter scheme, and (as far as is understood), the seasonal forecasts do not use the same stochastic representations as the medium-range ensemble. The climate-change (e.g. UKCP18) forecasts rely on fixed parameter perturbations which are not used on shorter timescales.

PF-R2: There is a need to understand the reasons for such “unseamlessness” and whether they are justified.

A seamless stochastic physics package (SKEB + SPT) for the global model has been developed for GA7. This is being incorporated in each system (NWP, seasonal, CMIP6) during operational implementation. UKCP18 uses fixed perturbed parameters as a deliberate attempt to explore climate sensitivity space, rather than necessarily reflecting the uncertainty in our parametrizations.

On the applications side, it was encouraging to see more and more applications of ensemble prediction for decision making. However, from the written papers at least, it appears there are still areas of concern at the forecasters level. How are ensembles used by forecasters? Do the ensembles adequately represent uncertainty, or do the ensemble probabilities somehow jump discontinuously from one analysis to the other?

PF-R3: A forecaster-based comparison of MOGREPS with the ECMWF ensemble would be helpful.

As discussed above there is on-going effort to improve the effective delivery of ensembles to operational meteorologists, and we shall consider this helpful suggestion in the effort.

Looking to the future, is it obvious that the most effective use of the Met Office medium-range ensemble system is a stand-alone system, particularly given the fact that the Met Office does not have the resources for a 50-member ensemble (and is therefore looking to combine ensembles from earlier analysis times – a somewhat unsatisfactory procedure for obvious reasons)? As an alternative, one could ask whether combining the Met Office and ECMWF ensemble members together into a multi-model ensemble might be the best option in terms of value for Met Office customers.

PF-R4: MOSAC proposes that this is something that could be studied: for example, is Potential Economic Value for a combined forecast system greater than for either system individually?

Perhaps we could clarify that many Met Office products use blends of post-processed multi-model (e.g. Met Office/ECMWF deterministic/ensemble) forecasts, and we are currently working with ECMWF (and other global centres) to make their data available in a common format for cloud-based post-processing. The use of shifting/blending forecasts is not an alternative to the multi-model approach, rather a way of providing additional value.

Regional and Global NWP

Resulting from sustained R2O investments in the areas of data assimilation and model physics, two major upgrades were implemented to the operational global NWP system (PS40 in February and PS41 in September) in 2018 that have led to significant forecast skill improvements. The PS41 upgrade included significant improvements in surface exchange parameterization and also for the first time includes the assimilation of all-sky satellite microwave radiances, although the impacts of such all-sky radiance assimilation may not be as apparent. There are also considerable efforts in the development of next-generation physical parameterization schemes, ocean analysis and forecasting, regional and urban scale forecast capabilities while a significant amount of new development is dedicated towards the next-generation modelling system LFRic. While MOSAC commends the UK Met Office science team in outstanding R2O research that maintains the Met Office's status as one of the top two premier global NWP centres in the world, the committee cautions challenges ahead, especially the development of the LFRic system.

RGNWP-R1: MOSAC would like to know more about the actual and contingency plans for DA development, with regards to the use of all-sky radiance, and the development of DA for LFRic, the coupled and holistic DA development from regional to global prediction, from weather to climate, from atmospheric to coupled environmental sub-systems, and the dependency on international collaboration. For the latter MOSAC would appreciate to be kept informed on the outcomes of the audit of the JEDI/Met Office collaboration that will be performed in the next few months.

See comments above.

One of the greatest future challenges is identifying sources of predictability at the subseasonal-to-seasonal (S2S) time scales and exploiting them in NWP systems. It is expected that the number of degrees of freedom that are predictable at this scale is significantly greater than the number at beyond seasonal time scales, but far less than the number of degrees of freedom for the complete weather prediction problem. Improved S2S prediction has the potential to open up a large number of truly novel applications with important socio-economic benefits. S2S forecasting depends on the initial conditions and coupling to oceans. It is fundamentally a combination of the already difficult NWP and climate prediction problems and it will need careful attention to the interaction of the different components of the Earth system. There is somewhat a missing piece in the forecast portfolio of Science with regards to S2S prediction.

Although operationally we are not currently operating in the sub-seasonal timeframe, it does form part of the research development of the global seamless coupled model (e.g. MJO performance). Furthermore, we are engaged in a number of research projects with partners that operate in this sub-seasonal timeframe and include use of 2-week coupled NWP, MOGREPS and GloSea. These collaborations include participation in a MJO task force, heatwaves (with KMA), Monsoon active-break cycle (WCSSP India project) and through UM collaboration with NCMRWF, and the North Australian Climate Programme (NACP) project on North Australian climate variability (with BoM and the University of South Queensland).

RGNWP-R2: MOSAC would be interested in having an update on sub-seasonal to seasonal activities next year if this is part of the future Met Office plans.

We are involved in a workshop with ECMWF and the University of Reading during March and anticipate that this will help inform our plans in this area. We would be happy to report back at the next MOSAC meeting.

For the global NWP perspective, traditional sub-grid scale parameterization of convection and gravity wave drag are entering a "grey zone" in expectation of global models with resolution close to 5km in 5 years or so.

RGNWP-R3: MOSAC would like to be presented Met Office plan to tackle the above matter.

We agree that this is an important challenge. The Met Office has made some progress in this area in recent years, with the introduction of an initial scale-aware "blended" boundary layer scheme in convection-permitting formulations of the UM (including UKV and MOGREPS-UK); playing a leading role in GASS greyzone cold-air ourbreak intercomparisons (Field *et al*., 2017), the follow-on GASS (sub)tropical intercomparisons (Tomassini *et al*., 2018), and leading work on the greyzone behaviour of gravity-wave drag parametrizations (Vosper *et al*., 2016). We are also running global climate simulations at greyzone resolutions (PRIMAVERA) and engaging with the international community in the EUREC4A project.

There is clearly much more to do but the new CoMorph convection scheme is intended to be scale-aware and suitable for use across a range of resolutions (~1 km to ~100 km). We would be very happy to update MOSAC with progress and plans at the next meeting.

The NGMS programme computing acquisition seems to not have taken the data assimilation specific needs into full consideration, like large IO, more frequency IO, and big memory needs. The DA framework will be another factor needs to be considered earlier on.

RGNWP-R4: MOSAC would like to be presented NGMS plans for DA.

See comments above.

The establishment of RMED is reviewed positively by MOSAC, since there are concrete, reported evidences of achievements and plns during the past year.

RGNWP-R5: The committee recommends that the regional scale NWP at least to UK region should investigate in more detail the cost/benefits of the sub-km scale, both of in terms of model physics, in particular LES and turbulence, and the methods and data needs for initializing sub-km scale forecasting. For example, how much evaluation and verification are done of the London Model? Moreover, for city-scale models, urban land surface data (e.g., building height, materials, tree cover) is not available in consistent quality for all UK cities let alone globally. The committee would like to see more integration of sub-km model development with the observation strategy, applied science, and O2R feedback from operational meteorologists.

We agree that the benefits of sub-km scale NWP warrant further investigation and that there are important issues such as land-use datasets, verification and initialisation to consider. This area will become an increasingly important component of the RMED research programme, especially as we begin to consider applications on the next supercomputer. We would be happy to report on progress in this area at a future MOSAC meeting as part of an update on regional modelling.

RGNWP-Q1: UK rainfall verification appears to be primarily against the rain radar network, but this also has inherent errors and biases. Is verification against other types of observations (e.g. rain gauges and satellite estimate) also still routinely carried out?

Verification against rain-gauge data is possible, where available, although representativeness errors can be large. It is also used to calibrate other sources e.g. radar, satellite precipitation estimates. Similarly, we use satellite estimates of rainfall in some of our work (e.g. GPM for tropical NWP) but issues e.g. bias, resolution present their own challenges.

RGNWP-R6: If regional models are to be used for high impact weather, then coupling with the ocean may be critical especially for coastal cities in tropical regions. It is welcomed that the UKEP team now sit within RMED – we look forward to seeing its application to more international locations, for which the data constraint issues might rely on good local partnerships.

Under the Newton Funded WCSSP India project we are developing an equivalent system to UKEP for India. We would be happy to report on progress in regional coupled modelling at the next MOSAC meeting.

RGNWP-R7: MOSAC notes the role of O2R (expert meteorologists) in diagnosing problems with the model that require urgent attention and encourages the model development teams to prioritize work in those areas (e.g. through PEGs) that are causing the Met Office's operational forecast services to be less accurate.

We thank MOSAC for this suggestion.

RGNWP-R8: MOSAC notes the needs of the R2O Team for tools and diagnostics to extract the information needed to understand and fix the problems in the NWP models, and recommends that diagnostic tools for process-level verification be developed and made operational to assist in the R2O process.

These process-based diagnostics of model problems currently sit within Foundation Science, as it is fundamental to the seamless model development process. MOSAC make an interesting suggestion that a common set of metrics and diagnostics are used to monitor the operational systems. We shall consider this suggestion through an internal workshop to discuss metrics/diagnostics and responsibilities across Weather and Foundation Science.

Support for observations research, which has a very good record of pull-through to model improvement, should continue with priorities that reflect the most serious gaps in physics understanding and simulation of regional and global NWP.

IMPROVER

IMPROVER will replace several separate post-processing systems with a modular open source post-processing system that is probabilistic at its core and verifies each step in the chain. Development started in 2016 and is well on track to deliver an alpha release in March 2019 with some data going to the Service Hub. It takes gridded ensemble outputs from a variety of sources (nowcasts, regional and global NWP), applies statistical corrections and neighbourhood processing before weighted blending in probability space. The resulting probability distributions can be converted to probabilities, percentiles, and ensemble realisations (using Ensemble Copula Coupling) which can be used to produce a variety of products for routine and high impact weather. IMPROVER was mentioned by several MOSAC presenters as being essential for getting the most benefit from ensembles (especially high resolution) in forecasting and warning. The system currently focuses on surface variables but will likely also include upper levels at a later stage.

MOSAC was pleased to note the progress made on IMPROVER since plans were introduced a few years ago and commends the open source approach that will facilitate collaboration and testing by interested centres such as the Australian Bureau of Meteorology. The committee was impressed by the design of the system, its well-ordered processing and stepwise verification, and the fact that it is scalable to run on advanced HPC systems. Some concern was expressed about the potential loss of useful spatial structure resulting from neighbourhood processing.

IMPROVER-R1: MOSAC encourages the further development and implementation of "smart" neighbourhood methodologies that are spatially adaptive and account for topography and local features (e.g. urban vs. non-urban, land vs. sea). Care will also need to be taken when blending inputs and models with different behaviours, for example nowcasts and high-res NWP and convection permitting and convection parameterising NWP.

See earlier response.

ParaCon

MOSAC was pleased to hear of the progress of the joint Met Office/NERC ParaCon programme – aimed at producing 'next generation' convection parameterizations and parameterization concepts. Three types of framework are being pursued: a generalised mass-flux approach; a turbulence approach aimed at the convective grey zone; and a more experimental multi-fluid approach. The paper and presentation focused on the new mass-flux scheme (CoMorph) which appears to have a lot of attractive properties and has been designed to fit into the Unified Model and be compatible with other relevant parameterization schemes, such as the microphysics scheme and a new cold-pool scheme. Some early results were presented. These were encouraging: convective rainfall appeared more realistic spatially and temporally (for a site in the Indian Ocean). There seemed to be well-designed plans for the second phase of ParCon, which will include full implementation of the CoMorph scheme in the UM, testing and evaluation. An international workshop on convection parameterization is planned for later in 2019.

Overall MOSAC was impressed with the potential of the CoMorph scheme. The new closure in the boundary layer appears clever and more realistic. However, we also had several questions and recommendations that the ParCon team should consider:

PC-Q1: How well does CoMorph represent convection across all the regimes where it needs to act? For example, within shallow convection regimes, within cold-air outbreaks, and within mesoscale convective systems where convective and stratiform clouds are present?

We were enthusiastic to present CoMorph to MOSAC this year, but it is still in the early phases of testing. Over the coming year it will be subjected to a number of climate and NWP style tests.

PC-Q2: The evaluations of CoMorph that were presented and planned seemed fine (e.g. during Terra Maris), but they were all in the tropics. Do you plan evaluations for the mid-latitudes and the polar regions?

CoMorph will be evaluated using data from a wide range of regimes.

PC-Q3: Do you plan to evaluate against process-level observations, e.g. against flux and profile observations (you only showed precipitation output from the UM simulation). This may provide insight as to how well the scheme is working.

As with all major parametrization developments, detailed process-based evaluation will be performed including TOA and surface flux comparisons, profiles of temperature, humidity and cloud properties (amount and optical depth), cloud top and base height, as well as dynamical coupling (e.g. in the MJO, AEW's, etc).

PC-R1: MOSAC suggests comparing the performance of the CoMorph scheme against other state-of-the-art schemes (e.g. that used in the ECMWF Integrated Forecasting System)? This could be done relatively easily in a Single Column Model or by simply comparing relevant aspects of some case study simulations with the UM and IFS. (We are not suggesting adding another scheme to the UM as this would be time consuming and not necessarily a fair test, given the tuning that is always necessary).

This is a good idea, which we shall consider as CoMorph matures.

PC-R2: Consideration should be given to the partition between resolved and parameterized convection, in the convective-scale configurations of the UM, including the trials of the 5-6 km global scale set up.

A key requirement is for CoMorph to be scale-aware, hence tests through the convective grey zone will be an important part of our trialling strategy for the parametrization.

PC-Q4: What are the other partners contributing to the ParCon programme? The paper and presentation only focused on the three new schemes. There are other projects within ParaCon – how are they contributing?

ParaCon is structured into six projects, each of which is led by a university researcher (but in several cases cutting across university groups):

1. Convection-dynamics coupling – led by John Thuburn at the University of Exeter. This is the development of the dual-fluid dynamical core, and supporting process research
2. Convective initiation – led by Doug Parker at the University of Leeds. This is process research using LES into the size, statistics, and organisation of convective updraughts, tracking their formation from the boundary layer into the cloud layer. This is expected to be used to improve initiation in CoMorph.
3. Fluid dynamics of updraughts and downdraughts – led by Michael Herzog at the University of Cambridge. This is investigating different representations for the vertical velocity, and entrainment of updraughts and downdraughts. For example, Steef Boeing at the university of Leeds has developed a model for the motion of condensing thermals. Again, the destination of this research would be in determining the best representation of the CoMorph vertical velocity representation.
4. Turbulence approaches – led by Peter Clark at the University of Reading. This is the development of the turbulence scheme.
5. Mass flux revisited – led by Bob Plant at the University of Reading. This is preparing to test CoMorph in multiple different configurations – to include numbers of updraughts, different closure formulations, whether and how prognostic behaviour leads to better representations of convection.
6. Simulations – led by Steve Woolnough at the University of Reading. This is to provide the underpinning simulations of different archetypes of convective behaviour to inform the process research in all other work packages.

PC-Q5: How is the internal effort at the Met Office for its in-house convection parameterization related to the ParaCon effort?

The development of CoMorph is very much part of ParaCon. As well as being a major scientific revision of the mass-flux scheme, it is also a re-write of the control structure for the code making it far more modular and flexible. Hence many of the other ParaCon scientific activities plan to use the CoMorph code structure to investigate and include different formulations for the mass flux representation, with extensive testing of the different assumptions currently being made within CoMorph, as well as testing of alternative formulations of e.g. the closure, representation of vertical velocity, the need for different numbers of updraughts, and the statistics that govern the initiation of new convecting mass.

PC-Q6: It does not appear that the two schemes being produced by external partners (U. of Exeter and U. of Reading) will be ready to be incorporated in the full numerical model within the lifetime of the project. Are there plans to do this in future?

The aim with the turbulence scheme is to arrive at a prototype, recommended formulation by the end of the programme, with evidence of performance within the LES model MONC. If this performs well, then it will be coded and tested within the Unified Model by Met Office staff perhaps beyond the lifetime of the programme. This approach has been adopted to ensure that the time is used to focus primarily on understanding the physical behaviour of different formulations, accepting that there is a considerable overhead to developing a flexible scheme within the UM environment.

In the case of the multi-fluid model, there is no current plan to incorporate the scheme into the UM within ParaCon. This is an entirely new approach to representing the sub-grid dynamics of convection, and as such, it is ambitious enough to arrive at a three-dimensional implementation in a stand-alone version of the code within the lifetime of ParaCon. The connection to the rest of ParaCon is at least two-fold for now – firstly the formulation of this scheme provides a route to combining conditionally-sampled approaches (such as the mass flux scheme) with volume-averaged approaches (such as the turbulence scheme), which we may choose to adopt as a route to unification of mass-flux and turbulence approaches. Secondly, we expect to use the scheme to understand in greater detail how convection couples to the larger-scale dynamics. It is possible we may choose to include mass sources from CoMorph to the dynamical core (as has been implemented at ECMWF). The multi-fluid model will be used to tell us under what conditions (or whether) this is a desirable approach. It is, of course, conceivable that having demonstrated multiple merits to the multi-fluid approach that we might consider an implementation, but it is expected this would need to be under a future programme of work.

PC-R3: MOSAC suggests that CoMorph should be be tested in data assimilation as early as its development allows. During the meeting, the Met Office itself indicated that it postponed changes that were improving the model because they do not seem to behave well in DA. Indeed, this can happen with such a new parameterization.

We completely agree and DA trials are planned very early on in the CoMorph testing, building on the lessons learnt around trying to implement our recent convection changes. We also recognise that changes to the representation of convection in our Perturbation Forecast model might be required as part of implementing CoMorph, together with re-calculation of the covariance statistics.

Large Scale Circulation Errors

The research on large scale circulation errors in the global model is an example of a very fruitful international collaboration that systematically compares commonalities between error patterns in global models. Through systematic diagnostics and numerical experimentation, the research has led to a deepened understanding of the root causes behind the errors. MOSAC is particularly impressed by the close collaboration between the Met Office and ECMWF (though perhaps this could be extended to study other parametrisations such as convection c.f. ParaCon). The focus has been on the sensitivity to surface drag formulations and parameterisations of orographic wave drag. Model simulations have revealed very large-scale impacts of changes in parameters within their range of uncertainty. By inter comparing parameter settings it has also been possible to identify compensating errors. The results so far are about to be published.

Further research in this area should be pursued, it should be investigated how data assimilation interacts with the model sensitivities and errors that have been identified.

LSCE-R1: Impacts on random forecast errors should also be investigated with more models, MOSAC was only shown results from UM.

We can discuss this with our collaborators at ECMWF. It could be considered as part of the GASS COORDE project, which is co-led by the Met Office and ECMWF

A specific question about the possibility of using DA ensembles as a way of estimating parameters in the surface drag and orographic drag parameterisations was put forward by the Met Office.

LSCE-R2: MOSAC thinks that this possibility should be investigated, earlier studies performed at Environment Canada, ECMWF and FMI could give some insight into the viability of using this technique.

This is an interesting idea, which we will consider along with whether there are ways to use machine-learning approaches.

The importance of momentum coupling between the atmosphere and surface, and the availability of very high-resolution simulations suggest that the representation of stratified flow over complex mesoscale topography is only very crudely represented in current wave drag schemes. Indeed, even conceiving the processes in terms solely of drag may itself be a simplification. Differences between ECMWF and Met Office representations of wave drag may play an important role in the apparent differences in propagation of information from the stratosphere to the troposphere in connection with stratospheric warming and tropospheric blocking events.

LSCE-R3: MOSAC thinks that the above discussion suggests it may be time to revisit these parameterisation issues.

We agree and will continue research in this area.

Observation Based Research

MOSAC recognises the excellent observational research work and effective pull-through into model development that was presented, clearly aligned with forecasting and model development priorities. It is essential to maintain quality in this area, as part of strategic intent to contribute to world-leading national capability for the science community. We look to an update next year as to the impact of reductions in capability on scope, and any changes in external partnership and community consultation on priorities that arise.

The Observation Research area has been significantly reduced in the past year due to budget limitations. Within these constraints the activities have focused on areas of historical strength such as airborne cloud measurements and are well-aligned with Met Office science requirements. However, the reduced participation in the FAAM aircraft facility will inevitably lead to a loss of influence that will not only reduce the level of participation in campaigns but also to those campaigns being less aligned with Met Office goals.

OBR-R1: This situation should be regularly monitored since the impact on the overall research effort will be only be felt over many years.

We agree and this situation will be monitored. In light of reduced capacity, we will continue to direct effort to ensuring OBR observations target the most pressing of Met Office problems. A number of ongoing and new initiatives, such as establishing the new advisory group, are intended to provide additional oversight to ensure this happens effectively. Pursuing airborne research objectives collaboratively with UK academia and international partners has been a strength historically, and we will look to continue to engage strongly here moving forwards.

OBR-R2: MOSAC suggests that given the reduction in flight hours, the new Scientific Advisory Group that has been established to prioritise future campaigns should anticipate opportunities for integration of model development and field campaigns at an earlier stage, e.g. ParaCon and Terra-Maris.

Agreed and indeed, in addition to prioritisation, one of the aims of the new advisory group is to ensure that the strategy and resourcing for exploitation of campaign data for model development is considered at the earliest stages of major airborne and ground-based field deployment planning.

It is essential that any reduction of FAAM instrumentation be done in early consultation with the wider atmospheric science research community, to identify changes in national capability. If there is a reduction in in-house resource rather than capability.

We recognise that any change to Met Office FAAM instrumentation has potential to affect the wider UK research community. Initial changes will involve retirement of legacy instruments and transfer of responsibility for selected instruments to FAAM. These changes have been discussed recently with NCAS/FAAM and the wider community via the FAAM instrument working groups. We do not anticipate further reductions leading to loss of capability at this time. Moving forwards, we will continue to engage with the wider research community regarding evolution of the Met Office instrument suite, both in terms of current instruments and future developments.

OBR-Q1: Which are the key partnerships and mechanisms that are crucial to maintaining access to cutting edge observations? Does the OBR group have time/resource for growing stronger national and international partnerships?

Strong national and international partnerships have been an essential part of our observations research work, and we recognise this as a key area for the future. Maintaining strong collaboration with UK academia, FAAM and NCAS is a priority, in addition to further pursuing international engagement for both airborne and ground-based work. OBR will direct resource to this accordingly, with necessary prioritisation to ensure we do not over-reach.

OBR-R3: We would welcome the MOSAC reviewing and enabling the external partnerships crucial to the OBR area.

We thank MOSAC for this offer.

MOSAC would like to review how OBR evolves within the context of an overall observational strategy, including operational observations and future UK network design. With increased focus on high resolution modelling, e.g. for aviation applications in urban areas, OBR can play a role in future observation network design where traditional surface observations are lacking.

Non-standard sources of observations are already being used in a forecasting context, but there will be an expansion of sources, e.g. from autonomous vehicles.

We agree that continued engagement between OBR and the Met Office Observations Programme (particularly Observations R&D) is important to ensure we fully utilise experience and capability across the groups. Although the end focus of the two groups is different (OBR being largely on developing process-level understanding for research and model development), there are clear synergies. We have some existing examples of how we are working together on selected projects e.g. in the airborne characterisation of water vapour sensors used on commercial aircraft, use of airborne cloud microphysical data to support radar hydrometeor classification scheme development and in the use of UK radar measurements for microphysics parametrisation evaluation. We will direct effort this year to exploring further synergies in strategy between the groups and opportunities for collaborative work.

Next Generation Modelling System

This year the Met Office presented a well-structured and coherent programme on the development work needed to prepare for exascale computer architectures to be available in the time frame 2024/25. The LFRic programme is planned to deliver a technically working version of a new scalable and computer efficient global and regional model by 2021/22 and a further 2-3 years is needed to prepare the models for operational implementation. This is a demanding but achievable time schedule. MOSAC thinks that this work is necessary in order to be prepared for the new computer architectures, a plan B was also presented where the present UM would be further developed. It is difficult to see how the present version of UM could be fit for purpose in a longer time frame, the polar problem will always restrict the global model resolution that can be achieved.

NGMS-Q1: The committee also feels that the computer upgrade in 2024/25 is the big step change and a question is how much effort should be put on the next computer upgrade planned for 2022. Would it be more effective to put less effort into the 2022 upgrade and compensate that with a bigger upgrade in 2024/25? It was difficult for the committee to make any clear judgement on this as not very much information was provided on plans for the 2022 upgrade.

Unfortunately, at this point in time Met Office are unable to provide details of the supercomputer upgrade plans because they are still in development and are commercially sensitive. However, we will be keen to discuss further with MOSAC at future meetings. Beyond this, the plans for following upgrades are unclear, and depend on a number of different factors such as the level of funding made available for the 2021 machine and future technological advances.

Another area of concern is the integration of the model and data assimilation developments into the NGMS framework. The LFRic programme focuses on the model developments and "separation of concerns" is mostly targeting model dynamics. It will be less effective on model physics as physics is not planned to be rewritten for this framework. The JEDI programme, essentially a US programme relying on the ECMWF and others OOPS project for the core DA algorithms, which was presented as the new programme for data assimilation integration, is not targeting scalability in the same way, and possibly not giving it the same importance, as LFRic does.

NGMS-Q2: How will the JEDI framework be integrated into the LFRic programme?

As discussed above, we are currently evaluating JEDI as a candidate for DA as part of the 'ExaDA' project within the NGMS programme. We have built a working interface between JEDI and LFRic, which has permitted the development of a nascent 4DEnVar capability assimilated radiances, radiosonde and surface observations. We are actively collaborating with both JCSDA (developers of the core JEDI system) and NCAR (who are in parallel developing an equivalent JEDI interface to MPAS). We are currently assessing a range of scientific, technical and governance issues that will inform a decision on the use of JEDI for NGMS beyond 2019. We will be happy to provide an update at the 24th MOSAC.

Furthermore, the committee would like to see more quantitative information regarding the priority of model spatial resolution s ensemble size vs model complexity. Some work has been done on using reduced precision to achieve a better computing performance, but this has only been introduced in a few components of the UM.

NGMS-Q3: Is there an overall plan for making use of reduced precision to get better performance?

As reported to MOSAC, plans are in place to deliver the ability to run LFRic in single precision by the end of this calendar year. There are then longer-term plans to ensure that we have the flexibility to run with mixed-precision.

References:

Field, P. R., Brožková, R. , Chen, M. , Dudhia, J. , Lac, C. , Hara, T. , Honnert, R. , Olson, J. , Siebesma, P. , de Roode, S. , Tomassini, L. , Hill, A. and McTaggart-Cowan, R. (2017), Exploring the convective grey zone with regional simulations of a cold air outbreak. Q.J.R. Meteorol. Soc, 143: 2537-2555. doi:10.1002/qj.3105

Tommassini, L. R. Honnert, G. Efstathiou, A. Lock and P. Siebesma (2018) Second phase of the “Grey Zone” project based on the EUREC4A and phase III of GATE field campaigns. WGNE/GASS white paper (https://www.gewex.org/gewex-content/uploads/2018/09/GASSWhitePaper_GreyZoneII_1Sep2018.pdf)

Vosper, SB, Brown, AR, Webster, S 2016: Orographic drag on islands in the NWP mountain grey zone. Q. J. R. Meteorol. Soc., **142,** 3128-3137, doi:10.1002/qj.2894