22nd Met Office Scientific Advisory Committee Meeting (8-10th November 2017)

Response from the Met Office Chief Scientist in red

Chairman's Report

Preamble

The 22nd meeting of MOSAC took place concurrently with the annual meeting of the Hadley Centre's Scientific Review Group (SRG). In his opening remarks the Chief Executive welcomed both Committees and set the tone for the meeting by declaring that research was *"at the heart of all that the Met Office does*".

MOSAC welcomed Professor Belcher to his first meeting as Chief Scientist, congratulated Simon Vosper on his appointment to the new post of Director of Meteorological Science, and noted Peter Stott's role as Acting Director of the Hadley Centre. Janet Barlow attended her first meeting as a MOSAC member, and Eugenia Kalnay and Gilbert Brunet sent apologies for not being present. A non-Executive Member of the Met Office Board (Dr. D.M. Burridge) and the Chairman of the PWSCG (Dr. W. Williams) attended as observers.

In the first set of presentations the Chief Scientist highlighted the Office's recent research accomplishments, the Deputy Directors overviewed developments and on-going activities in their particular domains, and the Chief Meteorologist reviewed from an operational perspective recent research initiatives and current forecasting challenges. A further 15 oral presentations and numerous poster presentations addressed specific aspects of the Office's research portfolio.

1. GENERAL REMARKS.

The overriding impression gleaned from this year's meeting was of an institution undertaking high quality research conducted by a dedicated and enthusiastic group of scientists. The high quality was evident by the Met office's continuing improvement of their already impressive research and forecast models, the enhancement of their notable publication and citation records, the breadth and depth of their national and international collaborative activities with other world-leading research institutions, and the retention of their second position in the ranking for global model deterministic predictions. The staff's dedication and enthusiasm was evident in the volume of the research output, the keenness to tackle new initiatives, the careful preparation of the briefing papers and presentations, and the open and vigorous participation in the discussions on the challenges currently confronting the Office's research.

During the year the Office has achieved several notable successes. Highlights include (a) the smooth upgrade to a new operational model cycle (PS39) providing 10/20 km (deterministic/ensemble) resolution for the global model and 1.5/2.2 km (deterministic/ensemble) resolution for the regional UKV model, (b) formal agreement on a new and sharply focused Hadley Centre Climate Programme, (c) noteworthy illustrations of risk-based assessment that link the Office's research with client needs, (d) introduction of hourly 4DVar data assimilation for the UKV model and (e) significant improvements in modelling tropical convection along with the opportunistic redeployment of the tropical regional model to provide encouraging ensemble forecasts for the 2017 Atlantic Hurricane Season.

We thank the committee for these very positive remarks.

Emerging issues of particular interest or concern include (i) the prospect of enhancing the 'virtuous-circle' linking research and operations, (ii) the need to develop a comprehensive business case for the procurement of the next HPC (circa 2020), and (iii) the magnitude of the task and the tight time-line for the completion of the Exascale project ahead of the acquisition of the subsequent HPC (post-2020 upgrade). Another matter of note is the issue of 'gender balance' within the Office.

MOSAC raise important points here:

(i) Motivated by the MOSAC report, Met Office has reviewed governance around research to operations and back to research. One outcome is the formation of a new group, chaired by Chief Operating Officer (and attended by Chief Scientist amongst others), which will oversee strategic development of new parallel suites. We would be happy to report on progress at a future meeting.

(ii) The first step towards making the case for the next HPC procurement has now been completed, with the development of a "Statement of Opportunity". We are now developing the timetable for the full business case, though concerns over the pace of technology advances in the supercomputing industry mean that there is some uncertainty over the target dates for procurement.

(iii) We agree that the Exascale challenge is significant. We are in the process of putting our Exascale Programme onto a more formal footing coordinated by a programme manager.

(iv) We acknowledge that gender and diversity balance was not properly considered in devising the speaker schedule at this year's meeting. Since the meeting the Met Office has submitted a proposal to seek Athena Swan accreditation. The Science directorate is considering what specific action it needs to take.

For convenience, the overview comments in the following sections are labelled under the banner of the four Directorates. However, it is recognized that some major activities, in particular aspects of model development, UM partnerships and the Exascale Project, are undertaken as joint efforts involving more than one Directorate.

2. Foundation Science.

The Foundation Science Directorate continues to advance the Met Office's capabilities to understand and model weather and climate across the range of space-time scales that characterize atmospheric and climate-related processes.

Modelling & Physical Processes: The Directorate has successfully met several goals related both to global and to regional modelling. Global model achievements include the successful PS39 upgrade of the operational models, and the refinement and demonstrable improvement in the representation of ocean-eddies (- achieved at considerably higher computational cost), and the simulation of the hurricane wake in the global coupled model. The proposed future developments are appropriate and include the somewhat overlooked but arguably pressing need to increase the vertical resolution, but there may well be a need to revisit these plans if there is a significant delay in delivering aspects of the Exascale project (- see later). The intensification of activities in 'Space Weather' forecasting and monitoring reflects this unit's growing international reputation.

Regional model achievements include the notable progress achieved using convection permitting (CP) models, and the amelioration of problems related to conservation properties and the use of the semi-Lagrangian technique. In particular, the progress recorded in using the tropical (RA-T) configuration is most commendable, and it is imperative that the Office establishes the physical basis that accounts for this improvement.

We are pleased that MOSAC recognized the progress we have made with CP modelling and fully agree that establishing the physical basis for these improvements is a high priority. The use of idealized model experiments is a key tool in this regard. We envisage further progress in this area in the coming year.

Use of CP models currently lies at the forefront of weather and climate research, but there are major challenges associated both with their further development and with their deployment in different geographical regions. MOSAC urges the Office to collaborate with institutions undertaking similar research elsewhere. Some of the challenges will be the foci of the forthcoming "GEWEX/NCAR Convective Permitting Climate Modeling Workshop". In light of the foregoing developments, the Office's extensive use of regional models placed at disparate locations around the world and their growing importance for Climate, the Office is encouraged to articulate clearly their 'Strategy for Regional Weather & Climate Modelling'.

We thank MOSAC for their advice in this area, and for alerting us to the GEWEX/NCAR workshop. We intend that some of our scientists will attend this. At the MOSAC meeting we articulated the rationale for our CP modelling and a strategy for model development. We recognize that this strategy for model development now needs to be used to set priorities for how the model is deployed for weather and climate applications in different parts of the world. We shall be pleased to provide an update at future MOSAC meetings.

Progress has also been made in the process-orientated studies of the COMORPH scale-aware convective parameterization project and the embryonic ParaCon project. The Committee urges the Office to tease out the mutual benefit that could accrue from exploiting the synergies between on the one hand these studies and on the other the development of CP models.

Our intention is that the scale-aware scheme will be implemented in future CP model configurations, on the basis that even at ~km grid spacings, some parametrization of convective clouds is still required. We should like to keep MOSAC abreast of these developments.

It will be appropriate for MOSAC to learn more of the ParaCon project as it matures.

We will be very happy to provide a more detailed update at the next MOSAC meeting.

The Office's high-resolution UM and LEM simulations to study the long-standing model defect of 'blobbiness' (- i.e. physically-unrealistic near grid-scale convective rain features), is illuminating. There is scope to better characterize / quantify the results using, perhaps, spectral diagnostics (- the feature itself can be viewed as reflecting a breakdown of scaling symmetries inherent to the underlying Navier-Stokes equations), and to address or ameliorate the problem by introducing near-grid scale stochastic noise.

We thank the committee for these excellent suggestions. We have already begun to explore these and continue to investigate this problem and explore possible solutions.

Technical HPC Issues: A major effort is being invested in the Exascale Project that incorporates as sub-components the restructured Gung-Ho and LFRic projects as well as the new GungHo Atmospheric Science Project (GHASP). An overarching goal is to reconfigure the Office's suite of models to enable it to exploit effectively the radical new architecture of future (mid-2020s) HPCs. It is patently necessary to pursue this goal, but its attainment is hampered by uncertainty surrounding the precise form of the architecture and it is rendered demanding by the seemingly tight timeline. In short, the risk factor for this ambitious Exascale project is, in its present form, high.

MOSAC commends the rigorous, stepwise, general approach adopted to address various technical issues and the physically well-founded and technically-feasible creative solutions devised for some key Exascale issues. (An example is the appealing concept of 'Separation of Concerns', although it will probably be difficult to apply it uniformly). This activity places the Office at the forefront of IT and HPC developments in this particular field. However, the Committee continues to stress that there remain major challenges (- for example those related to coupling physics-dynamics components, data assimilation, and shared numerical codes). Further MOSAC cautions that project completion might not be achievable within the presently set time-frame, and urges the Office to establish strict additional milestones and to consider devising an achievable alternative plan.

We agree that the risks associated with the Exascale Programme are high. We note here that both the model (LFRic and GHASP) projects are on track and over the next year we anticipate progress on some of the other important aspects, including physics and DA. The nascent Exascale Programme will instill formal programme management across the key projects, with clear milestones.

The uncertainty regarding the progress of the Exascale project also impacts upon the pending and pressing need to develop a comprehensive business case for the procurement of the next HPC - currently scheduled for circa 2020. The Committee believes it would be prudent to develop and assess carefully the full implications of a fall-back strategy that would involve operating with and evolving the EndGame configuration of models into the early 2020s.

The aim is to go operational with LFRic toward the end of the lifetime of the ~2020 HPC. While the ~2020 HPC will provide a development platform for LFRic, the modelling basis for this machine will be primarily aimed at the UM, and thus further optimization of an ENDGame-based UM will undoubtedly be required. We recognise, however, that directing too much effort on the UM optimization will inevitably slow progress on LFRic.

There will of course be some delicate decisions to be made about when, for example, physics developments should focus on an LFRic solution and break with the UM code-base, but it is also the case that beyond a certain point pursuing both a revolutionary path and an evolutionary one at the same time will not be tenable. This topic is subject to current debate.

We would also note that certain optimizations of the UM will likely continue and be ported to the mid-2020 machine (i.e. the one that follows the ~2020 procurement). The transition to LFRic (as shorthand for the full Exascale system) will inevitably be phased.

Field Campaign and Observation: MOSAC endorses the Office's participation in COALESCE3 and MACSSIMIZE, its proposed contribution to various forthcoming campaigns, and its 'remote' engagement in DEEPWAVE (- via the use of Met Office models to provide detailed regional forecasts and subsequent evaluation using the field observations). It is worth noting that the Met

Office has admirable field-observational capabilities and can devise plans with a longer time-horizon in comparison with many academic institutions. In principle this enables it, should it so chose, to take the lead in the design and planning of a major international field campaign, and thereby benefit from the added-value that can accrue from aligning the research programmes of other participating institutes to key Met Office objectives.

We thank MOSAC for this recognition. In recent years we have initiated several airborne and ground based observation campaigns that have benefitted from the subsequent involvement of external institutes. Examples include the ICE-D, COPE, COSMICS, COLPEX and LANFEX projects. The MACSSIMIZE campaign in March 2018, which will form part of our contribution to the Year of Polar Prediction, is another example of a campaign that we took a leadership role in initiating and which has since attracted national and international collaboration that will bring added benefit.

In the realm of R & D Observational activities, highlights included a case study of the added-value to be gained from utilizing the suite of surface, dual-Doppler radar and satellite observations. An overview of the UK network development set out the range and nature of the (potentially) available ingredients and the corresponding selection criterion. Notable efforts in this context are the continuing work to exploit "Mode S" aircraft data and the development of the new lightning detector. MOSAC welcomes the appointment of a UK Observations Network Design Manager, and emphasizes that the design should go hand-in-hand with regional model developments and DA constraints. Failure to retain/recruit suitable software engineers will become a particular concern if it is deemed important to ingest non-traditional data sources.

We thank MOSAC for these comments, and recognize the need to retain scientific software engineers in this area.

UM Partnerships: Forging UM partnerships with other national weather services is proving to be of considerable benefit to the participating parties, and activities span the range from global to CP modelling. MOSAC applauds the greater involvement of partners in model development. This in turn has demonstrated the complementary strength of the partner institutions and their contribution to pivotal aspects of the Office's own research programme. The geographical location of the partners combined with the improved performance of CP tropical models underscores the potential for the Met Office to take a lead role in developing tropical CP regional models and data assimilation schemes tailored to the tropics. There are issues to be explored regarding the lack of visibility of European collaborative efforts, and the strategy for selecting and for determining the optimum number of partners granted the need to keep the partnership scheme manageable and effective.

We thank MOSAC for these positive comments. We note that European collaborations are generally coordinated outside the partnerships team, and so may not have been visible at this year's MOSAC meeting. We would be happy to report on these collaborations at a future meeting.

3. Climate Science.

The *Climate Science Directorate* is recognized as one of the world's leading institutions in the field, and the advances achieved in the past year serves to undergird and enhance its position.

A landmark development of the past year has been the agreement on the Hadley Centre's new Research Plan. Its four foci reflect perceived needs in this area, but do not map directly onto the existing Hadley Centre structure. MOSAC recognizes that the evolving international framework

for Climate Science now places an increasing emphasis upon the development of 'Climate Services', and acknowledges the appropriateness of such a development. However, it also asserts that further fostering of high quality fundamental climate science research is essential for the effective future development and use of Climate Services.

We strongly recognize the importance of further fostering of high quality fundamental climate science research to sustain development and use of climate services. This requirement has informed the design of the new HCCP which is heavily weighted towards underpinning science. At the same time, we have designed a much more integrated mechanism for pulling through scientific advances into climate services. In this way we aim to accelerate the development and use of climate services whilst maintaining a healthy development of underpinning science.

Plans are in an advanced stage for the Hadley Centre's contribution to the next Coupled Model Inter-comparison Project (CMIP6). It was noted in last year's report that the Centre's model, with its sophisticated aerosol package, was exhibiting characteristics (such as climate sensitivity) that deviate from the mean of other models scheduled to participate in CMIP6. The magnitude of the deviation is notable, and it would be prudent that the Office conduct intensive further examination to explicate, as far as possible, this aspect of the model's behavior ahead of their participation in CMIP6.

We agree with MOSAC. An important focus of our work for CMIP6 over the next year will be to evaluate and understand the new Hadley Centre climate model including its climate sensitivity.

One major feature of European activity is the Copernicus Climate Change Services (C3S), and the Committee would welcome further information on the Office's participation particularly as it constitutes a vehicle for enhancing the Office's climate service capabilities.

The Met Office is a provider of significant elements of the pre-operational Copernicus Climate Change Service (C3S). These include:

- Seasonal forecasts out to 6 months ahead (as part of a multi-model system);
- Access to Met Office climate projections through the IPCC "Climate Model Intercomparison Project" (CMIP5/6) data centre based in the UK;
- Long time series climate data records (CDRs) for sea surface temperature;
- Leading the digital recovery of old data for the development of CDRs pre-1970s;
- Partner in the development of a roadmap for regional climate projections for Europe;
- Partner in the development of climate services for specific sectors (water and agriculture).

There are a number of related H2020 and ESA activities which aim to pull through R&D into Copernicus Service evolutions, in which the Met Office is involved. These include:

- The ESA CMUG (Climate Modelling Users Group) project led by the Met Office.
- Climate Attribution as a new C3S service. The Met Office leads the pre-operational development initiative EUPHEME, as part of the H2020 ERA4CS (European Research Network for Climate Services).
- Leading the H2020 EUCP (European Climate Projections) project, which aims to develop a set of harmonised regional climate projections for Europe.
- Leading the H2020 Coordination and Support Action project, Climateurope, which coordinates major European climate initiatives across Europe including C3S.

- Membership of the DG RTD expert team advising on the implementation of the "European Roadmap for Climate Services".
- Leading the development of land surface temperature ECV Climate Data Records (H2020 project EUSTACE).

Other Climate Science issues relevant to MOSAC will be discussed separately in the report of the Hadley Centre's Scientific Steering Committee (SRG).

4. Applied Science & Scientific Consultancy.

This young Directorate underwent several major reorganizations during the first few years of its existence, but the past year has been one of comparative stability. Within this environment the Directorate has blossomed as a customer-orientated science-based entity delivering greater engagement between the Met Office and its stakeholders and customers. It has become an admired major differentiator of the Office in comparison with other national weather services.

The Directorate has a well-founded assessment procedure to evaluate the desirability of undertaking specific projects and an impressive list of clients. During the past year it has achieved several notable successes such as its application of cost / loss analysis to a specific environmental issue, an approach to estimating extreme drought conditions, the development of numerous science-based marketable products, and studies related to global food security and advice to the health sector. The latter studies are potentially of considerable benefit to developing countries, and the Committee encourages the Office to collaborate with international funding agencies. Another noteworthy feature is the attention being given to building relationship and trust with the customers.

The Office will need to draw upon the Directorate expertise as it embarks upon developing a 'Research-Operations' virtuous cycle (- see later). Likewise, the Directorate's extensive list of customer contacts can help enhance the Office's research foci. Examples of the latter include the formulation of sea-component of the EPUK coupled model to better inform offshore industrial applications, and the selection of a norm when generating ensembles for the high-resolution prediction models.

Topics that have hitherto not been the subject of detailed discussion in MOSAC meetings relate to the issues of the evolving approach to targeting specific industries and the exploitation of the Office's seasonal forecasts.

We thank MOSAC for these very positive comments on the development of Applied Science. We will be happy to provide more information at the next MOSAC about alignment of Met Office Science and Business strategy and how we are utilising seasonal forecasts in the services.

5. Weather Science

The Weather Science Directorate is tasked to develop and deliver the Office's operational capabilities for weather, oceanic, and atmospheric dispersion and air quality forecasting, and to conduct research that underpins, informs and enables that overarching aim. During the year the Directorate has been restructured to better reflect its research objectives.

'Weather Science' engages heavily in joint research with other Directorates, and examples include the PS39 upgrade, the furtherance of the Exascale project, and the execution of several

international initiatives related to regional modelling. Some highlights of the Directorate's pursuit of its own objectives are the establishment of the R2O strategic area (see below), and the commendably agile and successful delivery of real-time ensemble forecasts for the 2017 Atlantic Hurricane Season (- that included encouraging forecasts of Hurricane Irma's track). This latter achievement is testament to the quality and remarkable portability of the 4.4 km regional model, and this portability has been successfully exploited in several other of the Office's initiatives. Another commendable activity of strategic importance is the new post-processing suite (- the IMPROVER project) because it is a bridge between the numerical suite and the provision of services.

The Directorate's research is evidenced in part by its excellent publication record, whilst the accumulated effect of its research is also reflected in part by the performance of the Office's weather prediction models. During the last year the conventional WMO/CBS verification metrics indicate that the global NWP model retained its long-standing position as second to the ECMWF, whilst concomitantly registering a modest improvement relative to the chasing pack and a slight decline relative to the ECMWF. Further diagnosis of these diverging trends is both necessary and challenging. For example, there was a striking improvement in this global deterministic metric during Summer-Autumn 2016 following the implementation of a variational bias correction scheme for satellite radiance assimilation, but this improvement was not sustained thereafter. It will be interesting to see the impact of the recent PS39 upgrade that included an increase in horizontal resolution. Forecast performance judged in terms of PWSCG criteria shows a slight positive trend for most variables but a decline in the quality of the precipitation forecasts. In contrast, there is evidence of a noteworthy improvement in the Office's forecast of significant ocean wave-height.

We appreciate the comments regarding trends in WMO/CBS scores and performance improvements generally. We agree that further CBS diagnosis is required, building on results already presented at MOSAC. We will work with other centres (esp. ECMWF) to explore NWP impacts elsewhere. One area of potentially increased effort/collaboration will be around all-sky radiance assimilation. We also note that the CBS metric is a relative trend so impacts seen in parallel suites e.g. VarBC do not translate directly to relative CBS scores as other models are also implementing major upgrades (and need to look over many months/years to assess significant trends).

Data assimilation: Achievements include the promised development and implementation of an En4DEnVar ensemble initial conditions for the global NWP, and the inclusion of several novel ingredients for convective-scale 4DVar. The clear demonstration of the effectiveness of the Office's hybrid 4DVar is gratifying for its developers and important for the model's performance.

The Committee believes the implementation of the hourly 4DVar for the global NWP model with overlapping 6-hour time windows could be substantially more demanding in computer time (arguably, up to a factor of 3 increase), and it would therefore be good to carefully evaluate its effectiveness. Data assimilation for CP models poses a range of new challenges, and the progress achieved to date is commendable. Appropriate but challenging plans are being developed for post-UM data assimilation schemes, and for ingesting land surface conditions. The scheme for the weakly-coupled Ocean-Atmosphere setting is approaching operational implementation.

We agree the concept of an hourly-updating, overlapping 6-hour time-window global 4DVar appears be costly. For a variety of reasons (effective preconditioning, number of observations assimilated in each cycle, operational scheduling, etc) we believe the costs can be significantly reduced from the x3 factor estimated here. We would be pleased to provide more information in future to MOSAC.

MOSAC recognizes that the hourly-cycle data assimilation being undertaken for regional model forecasts provides a valuable data base for Nowcasting, and ponders to what extent is this data set being exploited for Nowcasting purposes. The Committee also recommends that for forecasts on this scale, the Met Office should (a) *ensure* that the development of data assimilation schemes be linked to the design of the future UK observational network, and (b) *explore* the effectiveness of ensembles dependent upon the analyses resulting from the hourly-cycle data assimilation, and not merely upon the driving model's ensemble. The case for using local data follows from noting that the onset and location of meso-scale convective activity can be sensitive to local flow and forcing features.

We agree with MOSAC that the advent of operational UK 4DVar provides a potential step-change in our Nowcasting capabilities. The direct 4DVar assimilation of radar reflectivities is a key next step, together with the IMPROVER activity to redesign out post-processing system to take advantage of advances in nowcasting science.

Weather Science has been at the forefront of efforts to resurrect the 'Rolling Review of Observation Requirement', not just for data assimilation but all uses of observations (model evaluation, post-processing, forecaster use). We will work closely with the newly formed UK Observation Network Design group in the Observations programme to develop new observation requirements.

We note that the UK ensemble (MOGREPS-UK) *is* centred on the high-resolution UK analysis, and so does make use of local observations. However, the ensemble perturbations with which that analysis is dressed contain only large scales from the global ensemble (MOGREPS-G). The introduction of small-scale uncertainty would require convective-scale ensemble data assimilation, which we are addressing in the next few years via the hybrid 4DVar -> En4DEnVar route that we have already taken in global data assimilation.

Research-to-Operations (R2O): Establishment of this strategic area is a welcome development. It aims at improving and formalizing the procedure for transiting a new model from 'Research-to-Operations'. The Committee expressed concern regarding the adequacy of the 2*6 weeks testing period. In its present form, the project appears to MOSAC to be orientated more toward evaluating the deterministic model configurations. However, the operational emphasis is becoming increasingly orientated toward ensemble-based products, and MOSAC questions to what extent the issues of 'model resolution versus ensemble size', and 'characteristics of the ensemble spread' feature in model evaluation.

We agree the final 2*6 week 'package' testing period needs to be longer, but we should emphasize this is merely one stage in the R2O transition. Typically hundreds of trials are run for 'component' upgrades, with downstream final evaluation over several months through the 'parallel suite' as a final check of the total system.

At MOSAC we presented the expanded, joint deterministic/ensemble dashboard that we propose be used in future to approve operational global NWP upgrades. This is a step towards a more comprehensive ensemble-based evaluation. A similar, but less mature, activity is underway for UK NWP based on the HiRA verification toolkit presented at a previous MOSAC. The testing/evaluation strategy for operational NWP upgrades is currently under review within the new R2O strategic area. As well as the ensemble dimension, the advent of operational coupled ocean-atmospheric NWP is likely to have a major impact on testing strategy in future. We would be happy to present progress at a future meeting.

The Met Office operational global NWP strategy has for many years been to move towards a single resolution coupled ensemble (with a target resolution of 5-10km). On current HPC, we have achieved 10/20km deterministic/ensemble at PS39. Depending on capacity/benefit, the next HPC (~2020) may allow us to reach a 10km ensemble. As for ensemble spread, the implementation of En4DEnVar to replace the ETKF plus larger ensemble size (late 2018) is expected to have a significant impact on initial spread. Activities to improve model spread include inflation via analysis increments and developments in stochastic physics. We would be happy to report on these in future.

The juxtaposition of the R2O presentation and the Chief Meteorologists plea for a stronger 'Operations-to-Research' link prompted discussion on how to further enhance the 'virtuous-circle' linking research and operations within the Office. MOSAC recognizes the desirability of facilitating such a procedure and encourages the Office to give it further consideration (- over and above the Office's current 'Science-to-Service' governance review).

We agree. As mentioned above, we have formally reviewed governance of the R2O function and formed for example a new group with senior representation. These governance changes will provide clearer mechanisms for steering the work of the new R2O team in Weather Science.

Satellite Applications: Satellite information is demonstrably a dominant feature in determining an appropriate initial model state. MOSAC congratulates the Office's continuing increase in the effective use of such data, and it endorses the stipulated priorities of further exploiting the existing data and improving the DA for the UKV. Upcoming challenges include dealing with the possible extension of IR and microwave satellite assimilation to an 'all sky capability', because full utilisation will require exploiting the accompanying high spectral and spatial resolution data. This in turn prompts questions related to the need to further refine the linear/adjoint model to enable all-sky radiance assimilation, and the necessary human resources.

See above – all-sky radiance assimilation is indeed one area where we consider working more closely with ECMWF will reap mutual rewards.

Atmospheric Dispersion and Air quality: The successful and demanding transfer of all 'Numerical Atmospheric-dispersion Modelling Environment (NAME)' operational services to the HPC will substantially facilitate future developments, and the number of national and international groups using NAME is a testament to its recognition as a major tool. An UK-wide 'Air Quality Strategy Review' is currently underway and there are issues regarding its scope, the limited availability of human resources, and the dispersed nature of UK research in this field. MOSAC notes the significant (- unrivalled in the UK) capabilities of the Office to undertake air quality simulations, and it asserts that augmented participation of the Met Office would substantial enhance the UK's capabilities in the field.

We thank MOSAC for these positive comments.

Verification: The construction, interpretation and calibration of metrics to evaluate the performance of the Office's prediction models is central to its activities, and such metrics can also be of some limited aid in diagnosing possible model shortcomings. Moreover, the arrival of rapid-cycle high resolution, deterministic and ensemble regional forecasts has highlighted the limitations of standard metrics. MOSAC has previously underlined the need for the Office to develop and test verification metrics that are physically well-founded, provide unambiguous information of model performance, and are suitable for evaluating ensemble forecasts.

For the global model, illustrations were provided of the dashboard approach adopted for the deterministic (ensemble) forecasts using RMSE (CRPS) to highlight differences between a trial system and a control displayed as functions of lead-time and model variable. Likewise, a dashboard-breakdown was presented of the Office's deterministic model performance relative to that of other Centres using its Key Performance Indicator (KPI), and it is currently proposed to adopt a similar approach for ensemble forecasts using a CRPS-metric. The Committee remains to be convinced that CRPS should serve as the ensemble metric for KPI, and invites the Office to keep an open mind pending further study.

The CRPS is used routinely as a measure of ensemble skill at a number of centres, including ECMWF. We will keep an open mind and work with colleagues elsewhere to explore best practice but would appreciate a little more detail on the nature of the committee's concerns.

For the regional deterministic UKV, ensemble MOGREPS-UK, and the CP models, the Office has at its disposal the attractive and novel HiRa verification framework. Its deployment has already allowed a direct comparison of the UKV and MOGREPS-UK, and thereby providing evidence of the latter's superiority. Further extension of the HiRa-based work incorporating its recent refinements is warranted. Likewise, the dis-inclination of bench forecasters to use MOGREPS products because of the seeming under-spread of the ensemble might point to the need to improve the method for establishing the initial conditions for the ensemble. Notwithstanding MOSAC recognizes that evaluating CP-scale forecasts is a difficult, community-wide challenge.

The Committee commends the breadth of research undertaken during the last year, and regards it as a pilot project that will serve to prompt a more definitive study.

As discussed above, the mechanism to update global initial condition perturbations is being radically updated in 2018 (En4DEnVar). This will affect UK spread through both lateral boundary conditions and initial (large-scale) perturbations. The additional introduction of small-scale perturbations for MOGREPS-UK via En4DEnVar is being considered for the medium-term. The planned upgrade to MOGREPS-UK ensemble size (18, updated hourly) is also expected to help.

An interesting new initiative, appreciated by the Committee, is the first step undertaken to explore the utility of using 32 bit precision for specific model components. This has the potential to use computing power more efficiently in future applications.

This work is related to the exascale project, as exascale machines are projected to have large power requirements.

7. Further Remarks

MOSAC applauds the changes introduced to the format of this year's meeting. These included more comprehensive overviews by the Deputy Directors, extended consideration of some key themes, and the opportunity for individual MOSAC members to attend some SRG sessions directly related to MOSAC's mandate. It remains to ensure a better ratio of presentation-to-discussion time. The poster session is proving to be an excellent opportunity for less formal detailed discussions with individual members of staff. Likewise, the 'early career scientist' slot is ably exploited by the presenters to showcase their research and useful for the Directorates to signal possible future MO initiatives. The choice of themes, if not the gender of presenters, is a testament

to the range and depth of MO research. It would be helpful for the Office to prepare a short (- one page) report for the next MOSAC meeting outlining their 'equality strategy'.

We acknowledge that gender and diversity balance was not properly considered in devising the speaker schedule at this year's meeting. Since the meeting the Met Office has submitted a proposal to seek Athena Swan accreditation. The Science directorate is considering what specific action it needs to take. As requested we shall prepare a short document describing our approach.

In the same spirit as MOSAC welcomed the fore-mentioned 'virtuous circle' concept linking Research and Operations, it invites the Office to also consider establishing a pilot project to exploit synergies between all four of its research domains. Two examples of suitable cross-cutting and cutting-edge themes are Blocking and the Madden-Julian Oscillation. Both exhibit space-time scales that are highly relevant to both 'Weather Science' and 'Climate Science', require exploiting either mid-latitude or tropical configurations of the CP models of 'Foundation Science', and potential predictability on these time-scales would open new avenues of application for 'Applied Science'.

We welcome these very interesting ideas. In the short term our focus on joint Research-Operations projects is likely to be on topics designed to address immediate concerns for UK weather forecasting (e.g. assessment of future model upgrades, UK convective storms). Of course we are already doing a lot of work, both internally and in collaboration on both these modes (blocking and MJO) on weather and climate timescales.

From an administrative standpoint, the Committee believes the time is now opportune for the Office to sharpen MOSAC's Terms of Reference regarding the term of office of members.

We agree and shall review and revise the Terms of Reference for MOSAC in consultation with the new chair of MOSAC.

In accord with its duties, MOSAC reviewed the Office's response to the comments and queries that it raised in last year's report. It concluded that the combination of written responses and subsequent actions addressed most of the points raised by the Committee, and it expects that the remaining points will feature prominently on the agenda of future MOSAC meetings. Finally, the Committee wishes to thank the administrative staff for its exemplary support in the run-up to, and during, the meeting.