Report of the 26th Met Office Scientific Advisory Committee Meeting (17-21st January 2022)

Response from the Met Office Chief Scientist in red

Summary

The 26th MOSAC hybrid virtual meeting was held the 17-21st January 2022. MOSAC presentations again showed the exceptional strength of the Met Office in research and development. We appreciated the forward thinking embodied by the different papers and the pre-MOSAC workshop on "Optimum balance between ensemble, resolution and complexity for different applications". The early career presentations, poster and carousel sessions were excellent. The agenda permitted us to explore new aspects of the Science programme and in great part provided responses to MOSAC's recommendations and questions from last year. These reflections and discussions will help prioritising future science programme objectives. MOSAC is quite keen to contribute to the identification of these overarching goals.

MOSAC applauds the Met Office leadership in technical computing for environmental prediction and climate science. Its initiative, both in terms of this latest massive commitment of High Performance Computer (HPC) resources and in terms of the innovative "software as a service" cloud-based approach to computation and data services, is unique and forward looking. MOSAC praises the Met Office on its plans to move towards net zero emissions, especially the ten-year contract with Microsoft which includes a green energy stance.

MOSAC was very impressed with the leadership and contributions of the Met Office during COP26. We are sure many staff contributed in numerous ways, so congratulations to all who did. The efforts here have been terrific. Bearing this in mind, MOSAC did not see a great deal of discussion of any planned changes in Climate Research strategy following the event.

In the following we provide the highlights of the MOSAC meeting. The associated recommendations and questions of the detailed MOSAC report in the Annex are referred between brackets (e.g., AS-R1).

We thank MOSAC for the time and energy during the meeting and the thoughtful comments and questions in this report.

Before going into the detailed questions, we make two more general sets of remarks.

Firstly, the question of the changing priorities for climate science following COP26. This important question is being actively debated across the climate science community. Our thinking is focusing on: 1) climate modelling to support mitigation and adaptation action; 2) monitoring change and tracking progress towards climate action goals; and 3) facilitating decision-led research and development of climate services. Progress will be reported next year.

Secondly, several comments within the report concern our long-term ambitions for the next supercomputer. The business case for the next supercomputer has a range of proposals for how to use the new machine. These proposals are most detailed for Gen1, and include thinking on ensemble size, extension into medium ranges, potential resolution configurations for global and regional models, and proposals for a relocatable ultra-high resolution system. The business case also described the benefits to services from these upgrades. MOSAC are aware that we have

also been very focussed on preparation for delivery of Gen2 of the next supercomputer, which will be cloud based and so requires re-engineering of our simulation codes (via the NGMS programme), and a transformation in approaches to storing and serving data. So there remains the question of the big opportunity that will be opened up with Gen2. There are three aspects to our response. Firstly, NGMS will allow the Met Office to take full advantage of Gen2 supercomputer capacity, and our new data platform, PRISM, will provide the technological platform to ingest user data alongside the hazard data produced by Met Office, and to harness machine learning and AI algorithms. Secondly, we are putting ensembles at the heart of all we do at Met Office, and a big fraction of the new machine will be devoted to improved ensemble generation. Thirdly, these advances together will enable impact-based weather and climate services, and will move us towards providing advice to manage and reduce the risks. Prompted by the questions put by MOSAC, we shall continue to refine these ideas during the course of the year, and look forward to reporting back at the next meeting.

Responses to direct questions are provided when numbered questions are posed, with some in this summary, and the remainder in the annex.

EDI/ Early Career Scientists

MOSAC commends the Met Office on its Equality, Diversity, and Inclusion strategy. MOSAC is looking forward to seeing progress over the years to come, noting that the leadership of topics submitted to MOSAC remains largely dominated by men (e.g., only one poster by a woman). MOSAC recognizes the efforts, seeing that all early career scientist papers were from women, but cautions against showcasing only women or people from a minority background in early career scientists. It is important to strike a balance so that the work environment truly brings equal opportunities to all.

We thank MOSAC for their comments on this important topic and acknowledge that more progress is needed. We are committed to formulating specific actions this year as described in the EDI strategy and would be keen to share progress with MOSAC at a future meeting. We would remind MOSAC that across the MOSAC/SRG sessions, overall 30% of the speakers were women (excluding the early career presentations). Furthermore, in total 40% of the posters were presented by women (the poster presentations were divided between MOSAC and SRG, so some of these were presented to SRG and not to MOSAC members).

Travel is at the heart of a research career. As the current travel limitations imposed through COVID continue to hamper the community's ability to travel, we recognize that tools for collaborations have greatly improved yet lack of face-to-face interactions is increasingly posing a challenge. This is likely even more critical for early career scientists who haven't yet had the chance to build external relationships. What are the long-term Met Office plans on travel and how do they line up with its net zero emission vision?

We are grateful to MOSAC for pointing out the particular importance of travel for early career scientists, and the tension with reducing carbon emissions. All directorates within Met Office have a carbon budget as part of our net zero strategy. We are currently designing travel policies and are looking to ensure early career staff have priority in the allocation of the budget.

Partnerships

The Met Office collaboration culture is outstanding and growing. This is demonstrated by the large number of countries with Met Office co-authored papers which has increased from 55 in 2018 to 77 in 2020. Its scientific citation impact is amongst the top peer organisations like NOAA, NCAR and ECMWF (see Annex III). The Met Office eagerness to collaborate and to share knowhow and expertise is reinforced with the quality and richness of its scientific membership (see Annex V). The quantitative value of Met Office partnerships to the science programme is estimated around £ 28m worth of net value (see Annex IV). This is clearly a positive story, but there is more to it: partnership is one of the critical factors for the Met Office to be in such a good leadership position, and to be able to leverage the latest innovations and to provide a world class competitive service.

P-R1 For next year's review, in view of the importance of scientific partnerships for the Met Office, MOSAC would like to understand how the scientific partnerships strategy is impacted by Brexit and what is the proposed future approach.

We have very vibrant collaborations with European institutions and scientists, which have thrived in part through EU funding mechanisms. The Met Office is active in bidding for new EU project proposals under the Horizon Europe and Copernicus programmes. At this time, arrangements for UK participation in these programmes awaits agreement between the UK and European Commission. At the same time, we have a growing collaboration with ECMWF, notably in ocean modelling, exploitation and processing of satellite observations, and data assimilation, as well as a host of other peer to peer collaborations. We would be happy to update MOSAC further at the next meeting.

Collaborative field campaigns. We are encouraged to see that the planning and execution of field campaigns is continuing under difficult circumstances. We are pleased to see the Met Office strongly involved in international activities to exploit the data under the GEWEX umbrella. Hence, we encourage the Met Office to continue to collaborate with partners in using its modelling systems away from the UK (FS-R2).

We are delighted to share the news that FAAM is now flying again (after a pause of 2 years due to COVID) and the Met Office led ACAO (mixed phase clouds) Arctic campaign is going ahead in March 2022.

Academic partnerships. The Met Office has been very successful in drawing academic researchers into close collaboration and has generated some new ideas with long-term value like the PARACON project. We see these as useful for bringing new and even transformative research and recommend that the Met Office continues to look for similar opportunities in other key areas (FS-R3).

We agree and shall look for further opportunities. See response to FS-R3 below.

The way forward with observations. MOSAC also encourages collaborations as much as possible at the European and WMO levels for developing methodologies to exploit opportunistic observations data, to share the lessons learned, and for coordinating access to these data (data flow, prices) and sharing data with the rest of the community (FO-R3).

We agree, please see full response to FO-R3 below.

Unified Model (UM) partnership. The baseline for acceptance of the next generation modelling system LFRic performance should be expanded to cover a sufficient number and diversity of HPC workloads as possible (e.g., different applications and resolutions). The impacts on UM partners of moving to LFRic should be considered and addressed (NGMS-R2).

We agree. Discussions have been initiated with UM partners on opportunities afforded by cloud computing and Gen2 supercomputing. Please see full response to NGMS-R2 below.

P-R2 The next pre-MOSAC workshop could be dedicated to the future way of collaborating in the new HPC and supercomputer cloud-based landscape and what it means for the UM partners in terms of benefits and challenges.

We welcome this excellent suggestion, and we would like to consider it alongside those from SRG. We would also note that useful discussion on this topic has already started within the UM Partnership.

WWRP and WGNE? The MOSAC paper on partnerships (26.16) was quite exhaustive in many aspects, but it is important to note two important omissions: World Weather Research Programme (WWRP) and Working Group on Numerical Experiments (WGNE). These two entities are well aligned with the Met Office mission and R&D goals. As an example, the Next Generation LFRic/Modelling System (NGMS) team would surely benefit from WGNE activities.

PR-3 Given the active past participation of the Met Office in these two activities; it is important that it maintains an effective participation in WWRP and WGNE.

We agree that participation in these groups is extremely valuable, and we do have presence. For example, Tim Graham is a member of WGNE, Marion Mittermaier is a member of JWGFVR, Joanne Robbins is a member of the S2S project steering group and Brian Golding co-chairs the HIW project steering group. Membership of such groups is on behalf of the UK, not solely the Met Office. Other UK (but non-Met Office) participants are also able to represent Met Office views. It is worth noting that membership of such groups is not something the Met Office has complete control over. The Met Office, as UKPR, can put people from the UK forward if we are aware of vacancies, however vacancies on WWRP groups are not always well advertised (in contrast to WCRP).

Numerical Earth-system and Weather-to-climate Prediction (NEWP)

MOSAC acknowledges the good progress made with NEWP systems. On the global side, it is good to see that the Met Office will be able to include a coupled ocean, finding results consistent with other centres including significant improvements in the tropics. But there is still much more to do (FS-R5). On the UK side, the Met Office is to be congratulated on reaching a point where it will be able to introduce direct assimilation of radar reflectivity. We are pleased to see that data assimilation team are more and more involved early in model development and we encourage this to continue (FS-R4, WS-R1). Last year we saw very impressive results from cloud and convective processes R&D with significant improvement according to a variety of measures. Although the results are very impressive, the path to operations seems long and complex, with many blocking points, as the experience with CoMorph shows. We recommend an agile process be employed to quickly solve any problems that emerge (CCP-R1 and R2).

We agree on the continued need to review the path from research to operations. As modelling systems become more complex, testing regimes become more demanding. We are in discussion with other centres, such as ECMWF to share best practise. We would like to report back on the model development process at the next MOSAC.

Re-forecasting. The Met Office did a great job in consulting the community and gathering lessons learned from partners who face similar issues. This is essentially a large cost/benefit analysis with significant implications on human and computing resources, and it should therefore be addressed carefully. From there, the Met Office may consider pilot studies to quantify the cost/benefit of the different options (RF-R1).

We thank MOSAC for raising the important issue of reforecasting. We are currently considering options for reforecasting as part of the use of Gen1 of the new supercomputer. For further details please see the response to RF-R1.

More verification. MOSAC notes that there was not a huge amount of quantitative material on performance presented this year and would welcome more next year. With all the efforts on various nowcasting projects and on improving the UK regional NEWP system including post-processing, it would be interested to see quantitative precipitation forecast comparisons between the different methods (WS-R3).

We thank MOSAC for the comment, please see detailed response to WS-R3 below. We shall be developing new measures for post processing verification this year.

Leveraging on the NEWP programme. MOSAC acknowledges the pioneering work done by the Met Office to develop and apply direct impact forecasting and impact-based forecasting (IBF-R1, R2, R3, R4, R5 and Q2). Companies such as IBM, Google, and AccuWeather are using data science and machine learning to directly link weather impacts to weather observations and forecasts. Some Met Office approaches use a similar principle. Are you competing in this space or are the customer sets quite different? (IBF-Q1)

We thank MOSAC for their comments on impact-based forecasting. We see private sector contributions in this field as complementary to Met Office work, rather than in competition. Many of the impact based forecasting approaches adopted by the Met Office are aimed at an expert user, particularly supporting National Meteorological Services. Please see a full response to the comments.

Applied Science. MOSAC is always pleased to see the dynamism of Applied Science, and the development of climate services for adaptation strategy. MOSAC nevertheless questions the almost complete absence of weather services, at least in the material shared with MOSAC. Applications are driven by funding opportunities, but MOSAC wonders if there is any pro-activity with customers to develop future weather services. Some areas, such as the energy sector, are increasingly weather dependent and interested in probabilistic forecasting, for example (AS-R1).

We regret that MOSAC gained the (incorrect) impression that Applied Science is not pursuing weather services. Applied Science continue to work closely with customers from a range of sectors to develop weather services. These include services to the energy, aviation, defence, rail, and road sectors. Examples presented this year were included in the Impact Based Forecasting and Seamless Marine Information papers as well as the posters on aviation (TAF) and connected and autonomous vehicles. More detail is provided in the response to AS-R1 below. We shall endeavour to emphasise the balance between weather and climate applications in future meetings.

Next Generation NEWP Systems. MOSAC praises the accomplishments in project management so far, especially the efforts to link early with next generation data assimilation (NG-DA) and Observations Processing Systems (NG-OPS) activities (NGR2O-R1 and R2). MOSAC is encouraged by progress optimizing LFRic computational performance over the past year. We applaud the Met Office's action to announce and begin planning for a workshop of invited outside HPC experts to review LFRic performance. We suggest that the workshop include discussion of LFRic costs relative to models in use at other centres represented at the workshop (NGMS-R1). The impacts on UM partners of moving to LFRic should be considered and addressed (NGMS-R2).

We thank MOSAC for their suggestions and are looking forward to the workshop on 17-19th May. Ensuring NGMS is fit for purpose for a wide range of users is important. In response, we highlight that the new NG-UX (User eXperience) project will roll out an LFRic tutorial which will help prepare partners to evaluate LFRic configurations, and we would especially welcome extensive involvement of the partners in the assessment of the GC5-LFRic and RAL4-LFRic configurations via the usual GC and RAL processes.

Path to High Resolution. MOSAC congratulates the various activities under this umbrella. Notably, the TenTen project offers the prospect of providing important new insights on climate processes. Also, MOSAC is pleased that its previous recommendation to firm up the planning for sub-km work has been acted on including the Paris 2024 Olympics work. In the long term, it notes that there are open questions as to the cost-effectiveness of routine use of extremely high-resolution models relative to more advanced post-processing, and it encourages the Met Office to consider this angle in its further work and other considerations related to verification, coordination, and vertical resolution. (PHR-R1, R2 and R3)

We thank MOSAC for their encouraging remarks and agree with the comments regarding cost effectiveness of ultra-high resolution in different applications.

Operational perspectives. MOSAC encourages the use of testbeds to improve modelling systems, forecasting processes, technology tools and systems used in forecasting. We encourage more participation from operational participants, users, and stakeholders (OPTO-R1 and R2). The testbed forecasts should be evaluated using subjective and quantitative approaches. This is particularly the case for nowcasting, which should be compared with existing numerical forecasts to understand the benefits of developing this capability for all seasons (OPTO-R3 and R4). Operational meteorologists and researchers should work together to design and implement an optimal set of diagnostics and visualisations, especially for high impact weather, and use the testbeds to explore the best ways to use this information in delivering forecast and warning services (OPTO-R5, 6 and 7).

We are pleased that MOSAC is supportive of the testbed concept and thank them for the specific suggestions, which hare addressed in detail in the responses below.

Future of Observations. The development of a strategic plan to provide guidelines for future observations investment, and especially for opportunistic observations, is an excellent initiative. MOSAC nevertheless wishes to make a few recommendations so that this work can lead to clear and meaningful priorities on the areas to be investigated: i) opportunistic observations in the context of nowcasting and NEWP (FO-R1); and ii) data assimilation and resilience of the observing network (FO-R2). MOSAC acknowledges the transformation of observation technology that is on-going for radio sounding, lightning network, surface network and radar network. It is a long term but necessary evolution.

In response to the feedback at the MOSAC meeting we have revisited our written plans for the future of observations. We agree that resilience of the whole observation system is business critical. This is reflected in our tiered approach to observations, and the importance that we attach to maintaining reference and baseline observational data. Using 3rd party and opportunistic observations *in addition* to our reference and baseline data provides some useful redundancy in the system.

Seamless marine information. MOSAC is happy to see an expansion of impact-based forecast to the marine environment. MOSAC notes that the skill of the underlying NEWP systems these rely on are important in this context. It is not clear that is considered in the process (SM-R1 and SM-R2). As products for marine information mature, capturing the many aspects that can impact decisions can help further develop these services. For example, the combination of winds, ocean current, bottom draft, in addition to wave information may lead to a different overall risk.

We are grateful for the interest shown by MOSAC. We agree that appropriate consideration (and treatment) of the skill of the underlying data is fundamental to any successful application, acknowledging that 'useful skill' is necessarily dependent on the specific user / decision. It is for this reason the methods presented were all rigorously built on this basis

Concluding Remarks

This hybrid virtual meeting was quite a challenge! The participant locations covered a wide range of time zones and temperature range (-30C in Montreal and +30C in Melbourne). At the end of the day: some were going to bed, some were taking their breakfast, lunch, or dinner. After almost two years of pandemic, the technical and administrative staff was clearly well drilled and in control. This meeting was a real achievement, arduous but very efficient. Kudos and many thanks to the team.

Finally, MOSAC would like to thank the Met Office leadership, speakers, carousel and poster presenters for their great work and collegiality. We find these meetings intellectually very rewarding. Hopefully next year we will be able to meet in person and to have corridor- discussions. So important!

Gilbert Brunet (Chair) on behalf of the Met Office Scientific Advisory Committee: Thomas Auligné, Natacha Bernier, Andy Brown, George Craig, Véronique Ducrocq, Beth Ebert, John Michalakes, and Ian Renfrew.

We thank MOSAC again for their comments and for working across time zones to create such a positive and constructive meeting. We sincerely hope that an in-person meeting will be possible next year.

Annex: Recommendations and Questions

Foundation Science

The paper and presentations again showed the exceptional strength of the Met Office in fundamental research, including the ability to pull the results through to model improvements. We are also pleased to see the initiatives to more effectively communicate these innovations.

FS-R1 MOSAC welcomes the forward thinking embodied by the preparation of a Roadmap for Foundation Science. The structure presented in the paper is appropriate, but the most important content is the scientific and technical developments you will identify. What is the "next big thing"? We should find a way for MOSAC to contribute.

We thank MOSAC for their interest in the FS Roadmap. The plan is to finalise a first draft in early spring 2022 and then seek feedback from across Science & Technology, other Met Office directorates, stakeholders, and partners. We would welcome MOSAC feedback.

FS-R2 We are encouraged to see that the planning and execution of field campaigns is continuing under difficult circumstances. The extension of the LIAISE observing period to capture the spring dry down is important to the campaign objectives. The planned evaluation of JULES using the campaign data is an essential part of the project. We are pleased to see the Met Office strongly involved in international activities to exploit the data under the GEWEX umbrella. Hence we encourage the Met Office to collaborate with partners in using the model away from the UK.

The new Ice Nuclei Counter (poster presentation) shows great promise, and we hope that it can be deployed on FAAM for ACAO and M-PHASE this year. The link to the NERC CloudSense programme provides an opportunity to leverage the work of the broader UK community.

Due to delays that were somewhat out of our control associated with the current round of FAAM new instrument installations, the INC will unfortunately no longer take part in ACAO. At the time of writing the instrument certification process is nearing completion and we expect final airworthiness sign off during March. We are actively engaged in the CloudSense projects DCMex and MPhase and plan to participate, with the INC and more widely, in the airborne campaigns due to occur later this year and subsequent analysis.

FS-R3 PARACON has been very successful in drawing academic researchers into close collaboration with the Met Office and has generated some new ideas with long-term value. We encourage the efforts to obtain funding to continue the collaboration. We see this as a useful model for bringing new and even transformative research into the Met Office and recommend that the Met Office continues to look for similar opportunities in other key areas.

We agree that this has been a very useful funding model and PARACON follows in the footsteps of the GungHo project, which used the same mechanism to deliver the basis for the next generation dynamical core in LFRic. We are currently developing plans with NERC for a new partnership proposal around next generation modelling at km and sub-km scales, including an observational component around the WESCON field campaign.

FS-R4 We were pleased to see examples of testing with data assimilation coming early in the model development process, but we would encourage developers of parameterisations to consider initialisation, spin-up and response to data assimilation carefully.

We agree with this recommendation and are keen to encourage more interaction between those developing the DA and those developing parameterizations. It is intended that JEDI will use Hybrid-TLM rather than the current PF-physics, hence we propose that this is something to work on in the context of NGMS.

FS-R5 On a longer time-frame we note that parameterisation development is likely to be one of the challenges in atmospheric science where machine learning may produce early benefits. We would encourage pilot activities to build competence in this area.

This is very much our intention. Currently, activities are limited by the lack of a generic interface between Fortran and data science libraries, however we have work nearing completion to resolve this technical issue and we aim to embed a knowledge of data science and its application within the parametrization team.

Weather Science

MOSAC acknowledges the good progress made this year towards PS45. On the global side, it is good to see that the Met Office will be able to include a coupled ocean, finding results consistent with other centres including significant improvements in the tropics. In addition, the ability to simulate sea-ice thickness is welcome and good to see a positive impact on sea-ice edge predictions. On the UK side, the Met Office is to be congratulated on reaching a point where it will be able to introduce direct assimilation of radar reflectivity. While for the first implementation this will be alongside rather than instead of latent heat nudging, it is still a notable landmark.

MOSAC recalls rather disturbing results from previous years indicating that the UK model with data assimilation performed less well after approximately 1 day than a simple downscaling model. This was attributed to less inaccurate initialization of the large scales than in the global model. It is therefore pleasing that PS45 includes a fix to address this issue, although whether it is a partial or complete solution to the problem is not clear.

WS-R1 MOSAC encourages the Met Office to complete further tests to (hopefully) confirm that, with the PS45 changes, data assimilation no longer leads to degradation in the regional model forecasts at longer range.

While not shown in the meeting, the DA in the UKV was evaluated before changes were made in PS45. However, a more significant body of work is planned in the coming year to look at the value of the data assimilation against a warm and cold starting system.

MOSAC notes the good progress with improver, including the interesting result that an EMOS approach is currently outperforming an ML one.

Looking ahead, there is clearly a lot of work to do in porting to the new supercomputer and in developing and transitioning to NGMS and NG-DA. While there will inevitably be resource tensions, MOSAC notes that it will be essential to find ways to continue to improve the quality of the NWP systems over the same period, primarily to deliver improved services but also to keep a sense of progress for hard-working internal staff.

WS-R2 MOSAC recommends elaboration and communication of a more detailed plan for NWP upgrades for observations, data assimilation, models (atmosphere and ocean) over the next few years.

We have clear plans on Gen1 of the new supercomputer for UM-based NWP, including technical upgrades to more easily accommodate new observations (via early implementation of JEDI-based observations processing) and plans for increased resolution, forecast length and ensemble size (for seasonal prediction). However, we do recognize that we presented little information about plans for the longer term (Gen2 supercomputer). While it is only natural that plans on longer timescales (5+ years) will be less detailed, we do intend to develop these over the course of the year and will be happy to report back to MOSAC at the next meeting.

WS-R3 MOSAC notes that there was not a huge amount of quantitative material on performance presented this year and would welcome more next year. With all the efforts on various nowcasting projects and on improving the UKV and Improver, it would be interested to see quantitative QPF comparisons between the different methods.

Our research plans for the coming year recognise the need to develop evaluation tools and metrics for nowcasting. We expect (subject to resource availability) to be in a position to report on comparisons between QPF methods by March 2023, although we also note that subjective evaluation (e.g. through the use of testbeds) is also important and likely to demonstrate more UK-relevant results than a relatively short term (months to 1 year) regional comparison between UKV and IMPROVER (MONOW) and other methods in the 0-2 hour forecast range. We also plan to develop a new set of metrics to quantify the value of IMPROVER post-processing more generally.

Climate Science

MOSAC were very impressed with the leadership and actions of the Met Office during COP26 in Glasgow. The co-leading of the Science Pavilion was a high-profile role and, by all accounts, was very well executed. We are sure many staff contributed in numerous ways, so congratulations to all who did. The efforts here have been terrific. There has been some discussion in the climate community, and during the MOSAC week, that COP26 has been another watershed moment for climate and humanities response to climate change. Bearing this in mind, MOSAC did not see a great deal of discussion of any planned changes in Climate Research strategy.

CS-Q1 Is the Met Office planning to make changes in climate research direction in response to changes in the research landscape post-COP26?

Indeed, the agenda for climate science post COP26 is evolving, moving away from defining the problem to more enabling solutions. In the 2021-24 Climate Science Programme agreed with BEIS we've already made a start with articulating our contributions (both leading and through partnership) to meeting these national and wider societal needs. Further changes to modelling strategy and outputs in support of solutions agenda are being discussed now along the following lines: 1) climate modelling to support mitigation and adaptation action; 2) monitoring change and tracking progress towards climate action goals; and 3) facilitating decision-led research and development of climate services. Progress will be reported next year.

MOSAC were pleased to see further developments in the professional development of science staff and on EDI considerations. The brochure was welcome and sets out how the Met Office has been raising awareness and developing its aspirations and values. The recognition that "equal opportunities" has more dimensions than gender balance is important. The brochure did not really cover actions, or the framework being used to make things happen. The points fed back to MOSAC during these discussions were well received.

Indeed, we were delighted to hear of the numerous activities and actions that have started recently and hear a little more about the framework you are now using. This applies particularly to leadership positions, where the need for greater diversity is apparent.

CS-R1 It might be beneficial to gather a paper for a future MOSAC/SRG on staff development - the specific actions and activities, as well as summarising any sort of assessment against KPIs that have been developed in this sphere.

We are happy to include a Science Profession developments paper next year to summarize ongoing actions in this area.

Applied Science

MOSAC is always pleased to see the dynamism of Applied science, and the development of climate services for adaptation strategy.

MOSAC nevertheless questions the almost complete absence of weather services. Applications are driven by funding opportunities, but MOSAC wonders if there is any pro-activity with customers to develop future weather services. Some areas, such as the energy sector, are increasingly weather dependent and interested in ensemble or probabilistic forecasting for example.

AS-R1 MOSAC would like to encourage, if not already existing, the elaboration of a global strategy to develop innovative services in the weather forecasting area, and for exploiting ensemble prediction, or very high-resolution prediction and nowcasting in line with the NWP supercomputer plans.

MOSAC does not have a clear vision of what is shared between the applications themselves and between the applications and other Met Office developments, including IMPROVER for example.

Applied Scientists and Consultants continue to work closely with customers from a range of sectors to develop weather services. These include, but are not limited to energy, aviation, defence, rail, and road. Examples presented this year were included in the Impact Based Forecasting and Seamless Marine Information papers as well as the Aviation (TAF) and Connected and Autonomous Vehicles Posters. In addition, the Applied Science paper provided an example of how techniques developed for our currently operational flight route prediction service have been reused to assess the impacts of climate change. These were chosen to provide variation from examples shared in previous years as well as to reflect the projects which have completed significant deliverables in the past year but do not cover our full range of activities. We would be happy to share a broader range of our weather services with MOSAC next year.

MOSAC is correct that opportunities are largely driven by funding opportunities. The Met Office is in the process of finalizing its Impacts and Benefits Strategy which will sit alongside the Research and Innovation Strategy. The Impacts and Benefits Strategy will provide a focus for where we seek to grow the impact of Met Office products and services over the next 10 years.

In the specific case of IMPROVER, data is not yet available for use in operational products, but we are carrying out initial investigations into its suitability for use in products for specific sectors. However, as IMPROVER was not designed with complex customer use cases in mind, we anticipate the need to complement its use with bespoke industry focussed post-processing for

some parameters and use cases. This approach was outlined in more detail last year in our Post-Processing strategy paper (MOSAC 25.13)

NGMS Programme

MOSAC is encouraged by progress optimizing LFRic computational performance over the past year. Algorithmic and code improvements yielded an impressive three-fold increase for the Basic-GAL configuration of LFRic compared to one year ago. The Met Office's responses to last year's MOSAC request for a report on progress and further work were exceedingly thorough and forthcoming. We understand that the Met Office currently estimates at least another factor of three more improvement is needed to meet the threshold for acceptance: that LFRic is no more than fifty percent more expensive than this UM baseline. Based on the presentations and additional discussions during this year's review, MOSAC appreciates that Met Office is working with great diligence and looks forward to future updates.

Information on LFRic scalability was not available in time for this year's MOSAC presentations; however, based on its formulation and construction, it is reasonable to expect LFRic will scale to processor counts and domain sizes unattainable by the UM. Success demonstrating scaling on large computing installations would represent a clear win for the program.

We applaud the Met Office's action to announce and begin planning for a workshop of invited outside HPC experts to review LFRic performance in response to last year's MOSAC recommendation [NGMS-R1&2]. the workshop will be an excellent opportunity to obtain expert feedback from outside needed for NGMS to meet performance, scalability and other technical objectives. Please rely on MOSAC for our input and feedback as plans develop for the workshop.

NGMS-R1 MOSAC requests another report for next year's review that includes computational profiles of performance (dynamics and physics), and time series showing the pace of improvement in overall performance and scaling. The report should also include findings and actions stemming from the LFRic Performance Workshop. We suggest that the workshop include discussion of LFRic costs relative to models in use at other centers represented at the workshop.

We agree with this recommendation. On the final suggestion though we caution that simple 'discussion' can lead to misleading results (e.g., differences in formulation (hydrostatic/nonhydrostatic), differences in complexity (often dominated by number of tracers), and the obvious consequences of differences in resolution and computational configuration). It might therefore be worth us exploring, as part of the workshop, whether the relevant attendees are happy to invest in the effort of a very light touch intercomparison of costs on a commonly defined test case.

NGMS-R2 The baseline for acceptance of LFRic performance should be expanded to cover a sufficient number and diversity of workloads that represent as many of the important NGMS applications and scales as possible. The impacts on UM partners of moving to LFRic should be considered and addressed.

The acceptance criteria, which were discussed at the last MOSAC/SRG, were deliberately chosen to span the wide range of applications that we run at the Met Office, specifically the high-end NWP forecast and the lower end climate prediction configurations. There is perhaps little to be gained by explicitly filling in the many configurations that lie within that span since these will be

picked up by the relevant science projects during their assessments (GC5-LFRic, RAL3-LFRic, NG-R2O and NG-R2C).

With regard to the UM Partners, the Met Office has invested significant effort in considering the partners needs and ran several early workshops to help them to start engagement with the work of NGMS. Positive outcomes from this investment were the creation of the NGMS Champions together with the emerging investment across the Partnership of about 4 FTEs of effort. Some of this effort is of direct help to the programme; some is directed at preparing the centres for transition. We would be delighted to see this engagement and investment grow further. The new NG-UX (User eXperience) project will roll out an LFRic tutorial which will help prepare partners to evaluate LFRic configurations, and we would especially welcome extensive involvement of the partners in the assessment of the GC5-LFRic and RAL4-LFRic configurations via the usual GC and RAL processes.

Supercomputer

MOSAC applauds the Met Office for its leadership in technical computing for environmental prediction, both in terms of this latest massive commitment of HPC resources and in terms of the innovative "software as a service" cloud-based approach to computation and data services under the ten-year contract with Microsoft. The contract's requirement that all power for the supercomputers come from renewable sources under its Net Zero strategy is further proof of Met Office leadership.

MOSAC appreciated hearing that there are "failsafe and third-party assurance clauses in the contract" with respect to Gen2 specifications and procurement and that the Met Office has "the ability to go out for third-party assurance to make sure [that we are] getting good value for money and to make sure that what's being offered [by Microsoft] is appropriate for our needs." Given that computing architectures and Met Office workload requirements will continue to evolve over that time, and as noted by the speaker [Selwood], this contractual flexibility will avoid the danger of speculating on Gen-II requirements five years in advance,

A key driver of the evolution of Gen-II requirements will be the high-resolution/ensemble-size/complexity cost-versus-value trichotomy that was the topic of the pre-MOSAC/SRG workshop and that provided a recurrent theme for the MOSAC and SRG presentations and discussions in this year's meeting. Another driver will be legacy requirements arising from the need to support the UM into Gen2.

S-R1 We recommend the Met Office undertake and maintain coordinated center-wide tracking and analysis of changes to requirements in the run up to Gen-II. This is needed to ensure that the Gen-II design provides appropriate balance of efficiency, productivity and performance across all important Met Office applications and workloads. Readiness for next-generation processors (GPUs) should be included in the ongoing assessment. We will look forward to updates during next year's meetings.

The Met Office supports this recommendation and is currently approaching management of such challenges and opportunities through four workstreams:

1. Technical and scientific collaboration already formed between the Met Office and Microsoft to explore the technical and workflow opportunities of running NGMS model initiatives on current and next-gen Azure architectures.
2. A Gen2 requirements development workstream has been formed under the governance of the Supercomputing Programme focused on development of scientific, technical and customer/stakeholder needs. This activity leads directly into the mid-term refresh proposals baked into the Microsoft Supercomputing Services contract.
3. An externally commissioned review of the global supercomputing technology market, service offerings, commercial and risk/reward opportunities is being commissioned. This is currently going through open procurement for initial delivery late in 2022 and will result in an independent market report produced bi-annually.
4. Existing contracted obligation of the supplier Microsoft to publish to the Met Office bi-annual (from operational service commencement date forward) projections of the scientific, technical, and service proposals likely to be submitted to the Met Office at the mid-term.

Path to High Resolution

MOSAC congratulates the various activities under this umbrella. Notably the TenTen project offers the prospect of shedding important new insights for climate. Also, MOSAC is pleased that it's previous recommendation to firm up the planning for sub-km work has been acted on (e.g., active engagement in planning for multi-national Paris Olympics work).

PHR-R1 In the long term, it notes that there are open questions as to the cost-effectiveness of routine use of extremely high-resolution models relative to more advanced post-processing (possibly trained on these models), and it encourages the Met Office to consider this angle in its further work.

We agree that the relative cost-effectiveness of extremely high-resolution models compared to advanced post-processing must be evaluated ahead of any operational implementation of the new model capability. This is within the remit of the R2O activity and hence P2HR will work with R2O to provide the evidence and capability of the high-resolution simulations in order that such decisions can be tested. We also have plans in place for example to explore the use of urban-scale modelling in context of providing training data for machine learning during the coming year.

The k-scale and global 5km projects are both, in slightly different parts of parameter space, looking at the opportunities and challenges (e.g., grey zone physics) on the path towards global kilometer-scale modelling. These are important issues that many centres are tackling, and is highly appropriate long-term research. The relationship between these projects (and indeed to the other path to high resolution projects mentioned above) was not entirely clear, and MOSAC encourages consideration as to whether there are any opportunities for consolidation or at least to expand cross-fertilization between the different efforts.

It also notes the challenges of obtaining statistically significant verification results in these very expensive simulations and encourages both continued thinking on how to get the most robust results (focus on representation of specific processes more than scores?) and transition to the hopefully more scalable NGMS system once that has reached sufficient maturity. It would also seem suitable in these long-term research efforts to fold in consideration of vertical as well as

horizontal resolution and, ultimately, to consider the data assimilation approach that would be required to take advantage of such models.

PHR-R2 Consider whether opportunities to rationalize or further cross-fertilize between projects under Path to high resolution umbrella are desirable.

The common research questions and cross-fertilization between the different projects under P2HR is part of the ongoing discussion within the P2HR activity and we agree that it is important for us to continually review their alignment. The Global5km and K-Scale projects have, for example, shared regular science discussion meetings including with UK academic partners working towards both global and regional domain contexts. One of the more unique contributions that the Met Office can provide in the research towards km-scale global and large-domain simulations is the capability to bridge traceably between global domain and limited area modelling across resolutions in order to advance understanding on relative costs/benefits of resolution, complexity (e.g., parameterziation) and domain size, and these research opportunities are being built into project work plans.

There were discussions of the benefits of higher vertical resolution in several presentations at this year MOSAC. But a coherent plan for taking this forward for either weather or climate timescales was not presented. There are clear benefits of higher vertical resolution for certain situations, for example, stable flows in moderate to complex orography, fog, orographic flows, etc., which could benefit all timescales.

PHR-R3 That plans for increases in vertical resolution are considered for a full range of applications.

Whilst we have not seen the clear benefits of higher vertical resolution described here in previous studies, we recognize that a new analysis of the value of vertical resolution is necessary as the standard models evolve in both physical processes and horizontal resolution (and domain size for regional model applications). The previous global model research has provided testing strategies for vertical resolution we can apply to model evaluation & development process (work by Andrew Bushell & William Ingram). For regional model development, the UKV operational model will move from 70L to 90L when RAL3 is implemented, and experiments have been conducted for urban-scale models running with up to 250 vertical levels. An ongoing challenge for demonstrating benefits remains to be model – data assimilation interaction, and relatively constrained domain sizes for regional model experiments. P2HR will consider the next steps for increases in vertical resolution across weather and climate timescales and can report back as part of the Foundation Science overview next year.

Operational Perspectives - Testbeds and O2R

MOSAC encourages the use of testbeds to improve modelling systems, forecasting processes, technology tools and systems used in forecasting, and appreciates that the early testbeds are largely to learn how to do testbeds.

OPTO-R1: The ratio of researchers to operational meteorologists was 20:1 in the summer testbed and 5:5 in the winter testbed. While acknowledging that different testbeds will have different purposes, to get the most operational benefit from testbeds all efforts should be made to have a critical mass of operational participants. The inclusion of trusted partners (e.g., from the

emergency management sector) in testbeds would further improve the utility of the testbeds to introduce those partners to the new capabilities so they can begin to be integrated into their decision processes, and to get constructive feedback.

We agree that all efforts should be made to have a critical mass of operational participants and we are aware of the difficulties in securing the appropriate resources for operational meteorology and intend to go through regular planning and review in coordination with the project board ahead of each activity. At the time of writing this, we have plans to include further collaboration with users in the next testbed activities (such as Met Office partners, media services team and Civil Contingency Advisors), subject to discussion with the project board.

OPTO-R2: MOSAC agrees with the point made in the paper that the effort to provide clear and effective visualisation, critical for the success of a testbed, is often underestimated. Adequate resources should be allocated for technical support from software engineers ahead of and during a testbed. To the extent possible, the visualisation of the new model or forecast products should use the same platforms as are used by operational meteorologists to facilitate their use and scientific evaluation and encourage take-up. This could mean making operational visualisation platforms available in the R&D environment.

We are due to revisit plans for visualisation requirements for testbed activities as a Met Office strategic action (Future of Operational Meteorology – FoOM) is to deliver a new visualisation system for operational meteorologists. We do recognize even with this there will be some bespoke visualisation required.

OPTO-R3: The testbed forecasts should be evaluated using subjective (survey) and quantitative (objective verification, measurement of forecast process improvements) approaches. This is particularly the case for (observation-based) nowcasting, which should be compared with existing numerical forecasts to understand the benefits of developing this capability.

Testbeds are designed to complement the objective evaluation of new modelling systems, which in itself is a major activity in the model development process.

OPTO-R4: Expanding testbeds to other seasons beyond summer and winter to sample a wider selection of high impact weather would be beneficial.

We agree that wider sampling would be beneficial. We expect in the future to plan the timing of testbeds around the capabilities and events being assessed.

OPTO-R5: The effective use of ensembles in forecasting operations remains challenging, and not just in the Met Office. MOSAC encourages continued efforts of meteorologists to lead in the design and development of practical, scientifically rigorous, ensemble-based tools and techniques that provide insights and facilitate the forecasting process, and report back to MOSAC on progress.

We are developing plans to explore the further exploitation of ensembles through the production chain and look forward to reporting to MOSAC on progress in the future. We would like to carry on using testbeds as an opportunity to develop the testing of these tools and this will be done in coordination with the new ensemble strategy.

OPTO-R6: IMPROVER has the potential to produce a variety of diagnostics to derive insights from a high volume of ensemble NWP. Meteorologists and researchers should work together to

design and implement an optimal set of diagnostics and visualisations, especially for high impact weather, and use the testbeds to explore the best ways to use this information in delivering forecast and warning services.

We agree. This was the framework in which the IMPROVER evaluation was conducted within the winter testbed: it provided an opportunity for researchers and operational meteorologists to work together and discuss the set of products and tools they would prefer to use to assess the severity of an event and how it impacted their ability of defining the likelihood, severity, and location of a warning.

OPTO-R7: Additional clarity on the impact of the Met Office's forecast and warning services on societal behaviour and how that information feeds back through O2R would be appreciated.

We welcome this recommendation. It is an interesting aspect that we will explore over the next year to consider how we can best integrate within the R2O-O2R construct.

Next Generation-R2O

MOSAC praises the accomplishments in project management so far, especially the efforts to link early with next generation data assimilation (NG-DA) and Observations Processing Systems (NG-OPS) activities, and address and mitigate risks.

It is encouraging that JEDI-based Observations Processing Application (JOPA) is on track to achieve its first goal to reproduce OPS capabilities. This is a crucial milestone that requires the team's full attention. The true success of this initiative will however be fully demonstrated when JOPA starts showing new and enhanced capabilities.

NGR2O-R1 We encourage the NG-OPS team to start planning for "quick wins", leveraging collaborative developments from external teams or using new software flexibility to implement new features.

During the development of JOPA to replicate the capability of OPS, several bugs were found in the old way of processing observations as well as improved ways to thin and quality control the observations for each observation type. The team has compiled a list of quick improvements across different observation types to harmonize the processing as well as updating the techniques themselves. We are aiming to implement such changes after the global implementation of JOPA. Plans are already forming on how to exploit the next generation satellite missions (EPS-SG and MTG) which was the primary driver for speeding up the development of JOPA. New features under discussions that will be more easily achievable in the new system due to its flexibility and modularity include: using slant path (rather than vertical columns) for radiative transfer calculations and GNSS-RO bending angles calculations, using 2D GNSSRO as observation operator, increase the number of radiance observations in all sky conditions, using ensemble information in the quality control processing of observations and coupling different Earth components through the observation operator.

The schedule change presented last year to postpone the implementation of NG-DA after LFRic model has released some pressure on the NG-DA team. It is also worth acknowledging the recent accomplishment of porting the background error covariance matrix. We however express some concerns about slight schedule delays and difficulties to sufficiently resource the team.

NGR2O-R2 Given there is little slack in the schedule, this may require particular attention to avoid delaying JEDI-based Atmospheric DA (JADA) implementation to Gen2 supercomputer phase.

We agree that attention is required to the development and implementation of JADA. To this end, we have decided to merge NG-OPS and NG-DA projects, NG-PAO (Processing and Assimilation of Observations), led by David Simonin, to resource JADA with skilled staff who have developed JOPA in the last couple of years. This will also be a fantastic opportunity to develop our people more in DA, by removing the artificial barrier created by having historically different software for pre-processing observations (OPS) and for assimilating observations (VAR). Moreover, we are in the process of replanning and re-prioritizing the development and delivery of JADA by focusing on the essential steps to create a competitive Ensemble of DA to initialize the future Ensemble Prediction System. The project is still particularly challenging due to the difficulty of finding people with skills in DA and C++. We are in the process of recruiting new DA staff who will need JEDI/C++ training before being able to contribute to the development of JADA.

Impacts Based Forecasting

MOSAC acknowledges the pioneering work done by the Met Office to develop and apply direct impact forecasting and impact-based forecasting. The Vehicle Overturning (VOT) model is becoming quite mature and is a vehicle (no pun intended) for testing ideas to improve impact forecasting. For example, investigation of the relative importance of vulnerability, exposure and hazard information on the predicted risk suggested further work is needed to improve vulnerability indicators. Results from tests on different ways to use IMPROVER input in the VOT will inform other impact forecasting applications like heat health, flood extent, landslide, etc.

IBF-R1: MOSAC would like to hear more about new developments and applications, including the most appropriate ways of processing numerical inputs for different impact forecasting applications.

Thank you for this recommendation. We agree that it is important for the Met Office to review different impact and risk-based forecasting approaches and determine their applicability for different types of applications and therefore users. This is considered and included in our future plans.

IBF-Q1: Companies such as IBM, Google, and AccuWeather are using data science and machine learning to directly link weather impacts to weather observations and forecasts. Met Office approaches using Decider use a similar principle. Are you competing in this space or are the customer sets quite different?

We are aware of work within the private sector in the field of impact modelling and rather than seeing it as competition we feel it is complementary and facilitates opportunities for collaboration. The use of data science and machine learning relies on sufficient high quality impact observations for training and evaluation purposes. All organisations mentioned are in excellent positions to manage and maintain such large datasets. Many IbF approaches adopted by the Met Office are aimed at an expert user, particularly supporting national meteorological services, and benefit from synthesis with additional experience and knowledge which we believe adds value to the process and the dissemination.

IBF-Q2: Impact forecasting approaches that make use of (dynamic) vulnerability and exposure information have the potential to be more responsive and accurate, assuming good vulnerability and exposure data are available. Does the Met Office have a strategy regarding its investment in statistical versus dynamical impact modelling approaches?

We agree that dynamic vulnerability and exposure is a useful and interesting next step for impact modelling and risk forecasting. We are currently working with partners at HR Wallingford under the WCSSP India project to determine how earth observation data can be used to support routine, near-real time assessments of changing vulnerability and impact. The aim is to use this data to provide updated vulnerability/exposure context for new flood impact model runs. Similarly, our new automated impact data methodologies and social sensing research, which are still in test, offer opportunities to understand the life cycle of impactful events (i.e. the drivers of socio-economic impacts, how people respond and how this changes exposure and vulnerability within and after events) which could be embedded into impact models and scenario assessments. We plan to build on these activities over the coming years to address critical questions: (1) workflow integration of this information within impact modelling and (2) evaluate dynamic vulnerability and exposure sources and their value to IbF and warnings.

IBF-R2: Hazards rarely occur in isolation. Future work should explore predicting the impacts from multi-hazard (for example, wind + rain) and compound/cascading events.

We agree and have two specific areas of focus which we hope to explore over coming years: (1) how multi-hazards and compound events influence impact assessment – we plan to review this using outputs from the VOT and the Surface Water Flooding (SWF) Hazard Impact Models and (2) appropriate mechanisms for visualisation, communication and dissemination of multi-hazard or multi-risk information. We are also interested in seeing how data science and Machine Learning might support this work, as preliminary investigations undertaken as part of the Met Office Machine Learning Community Practice OpMet Traffic Challenge, suggests that leveraging these methods may be beneficial for multi-hazard impact assessment.

IBF-R3: To build capability to routinely evaluate impact (-based) forecasts, support the development of machine learning-based approaches, and enable weather and climate impact studies, we recommend continued collaboration with university and other partners to develop methods to extract accurate information on observed impacts from online sources.

The examples of successful capacity building and co-production of impact-based warning services presented at MOSAC-26 demonstrate the value of partnerships in making impact-based forecasting accessible to other parts of the world.

We agree and have plans to continue and expand our collaborations/partnerships over the coming years.

IBF-R4: Partnering with economists and social scientists in international development projects, through partnership funding such as WCSSP, would be useful to evaluate the costs and benefits of impact-based warning services in mitigating the harmful impacts of weather and climate events. This information might help secure support for the ongoing provision of impact-based warning services in developing countries.

We agree that partnering with economists and social scientists is important for assessing value and benefit of impact-based warning services. The Met Office continues to maintain links with the WMO World Weather Research Programme (WWRP) Societal and Economic Research Applications Working Group and is an active participant in the HiWeather's Warning Value Chain

Flagship Project which is aiming to review value chain approaches to evaluate the end-to-end warning chain. We are keen to leverage expertise from these activities to inform how we can assess the value of our impact modelling and impact-based warning services.

IBF-R5: Social science evaluation approaches, again done in partnership, could also be used to help understand and improve how people behave in response to impact-based warnings, with this information feeding back into improving impact-based warnings.

We agree and as such are working with experts in experimental psychology at University College London as part of the WCSSP South East Asia Project to better understand how forecasters and stakeholders perceive weather-related impacts and the implication of these perceptions on interpretability of impact-based forecasts and warnings. This collaboration is planned to continue with a further exploration of the severity bias in impact-based warning issuance, as well as a review of impact severity classification and the difference between perceived impact severity and observed impact severity, with the aim of determining how severity assessment and communication influences responses.

Future of Observations

The development of a strategic plan to provide guidelines for future observations investment, and especially for opportunistic observations, is an excellent initiative. MOSAC nevertheless wishes to make a few recommendations so that this work can lead to clear and meaningful priorities on the areas to be investigated:

FO-R1 From the perspective of using opportunistic observations for data assimilation, nowcasting, verification and others, MOSAC encourages to work closely with expert teams in these areas to conduct impact studies or to get their recommendations. It is required for evaluating the benefit of a new data set on the quality of numerical prediction and/or for nowcasting. This work should also lead the teams to consider the question of the current use of the observations already available: are we already using these observations to their full potential and in an optimal way?

We are working closely with experts in the relevant teams to understand and prioritize their requirements for new observations. This work will feed into the observations 5-year strategic plan enabling us to target our efforts on the most impactful areas. In terms of impact studies, we will plan to conduct these when appropriate, however we note that it typically takes 5-10 years of development before a new observation type is sufficiently mature for a DA impact study. It is also worth noting that we see most initial benefits from opportunistic observations emerging from applications other than DA (such as nowcasting, verification and post-processing).

We welcome the comment regarding the current use of observations which are already available. A key focus of the new observations theme in the Research & Innovation Strategy will be to continue to deliver optimum value from existing observations.

The Observations Network Design team continue to support both the requirements gathering and the benefit assessment of non-satellite observations, using tools such as FSOI.

FO-R2 In addition to the analysis of the value of each type of observations, a risk analysis is recommended for the selection of opportunistic data. One risk is the long-term access to these data, which is not necessarily critical for situation monitoring, but more for data assimilation and even more for climate. It would be relevant to conduct an analysis of the resilience of the whole observation system and especially for data assimilation. The shutdown of aircraft data during the pandemic reminded us of the need for some degree of redundancy.

Thank you for the feedback. We agree that it is important to conduct a formal risk analysis regarding long-term availability of any 3rd party & opportunistic data. We agree that 3rd party and opportunistic data are unlikely to be a satisfactory source of data for climate monitoring due to the variable quality/availability of the observations, and this is one of many considerations that underline the importance of maintaining suitable reference and baseline observation data. We agree that long-term access to observations is critical for some use cases, such as DA, but less important for others, such as for situational awareness.

We agree that resilience of the whole observation system is business critical. This is reflected in our tiered approach to observations, and the importance that we attach to maintaining reference and baseline observational data. Using 3rd party and opportunistic observations *in addition* to our reference and baseline data provides some useful redundancy in the system. For example, in the recent pandemic the availability of opportunistic MODE-S data and SPIRE substantially decreased the impact that we experienced as a result of decimated AMDAR availability.

FO-R3 MOSAC also encourages collaborations as much as possible at the European and WMO levels for developing methodologies to exploit opportunistic observations data in order to share the lessons learned and for coordinating access to these data (data flow, prices) and sharing data with the rest of the community.

We strongly agree with this view. We are engaging with the EUMETNET community on existing opportunistic observations (e.g., MODE-S, citizen observations and GNSS) and actively collaborating to share additional data, know-how and processing responsibilities. We are also engaging with WMO in an expert group on UASs.

We need to find ways to continue to engage with the European community beyond EUMETNET on activities such as urbisphere, although this has become somewhat more challenging following Brexit. We would also welcome co-creation with MOSAC members of additional initiatives in both WMO and EUMETNET to work even more collaboratively in the 3rd party & opportunistic observations space.

MOSAC acknowledge the transformation of observation technology that is on-going for radio sounding, lightning network, surface network and radar network. It is a long term but necessary evolution.

We are grateful for this recognition.

<u>Convective and Cloud Processes Model Development</u>

CCP-R1 Last year we saw very impressive results from CoMorph with significant improvement on a variety of measures, so it was disappointing to see it left out of GC5. Especially with the constraints of NGMS, it is important to make sure that key developments don't get trapped in a long queue and we urge the Met Office to be flexible where it can be.

As discussed at the meeting we are reviewing model development process and decision making/governance with a view to maintaining agility to both rapid developments in science as well as efficient pull through of longer-term developments such as CoMorph and CASIM (see CCP-R2 below). We will look for further opportunities to implement well tested and robust science on the Gen1 supercomputer during 2023-2027.

Excellent example of physical understanding leading to model performance improvements – as with CoMorph, we recommend that the Met Office take an agile approach to bring CASIM and the associated model updates into operations quickly.

The new cloud parameterisation is an excellent example of physical understanding leading to model performance improvements, as well as being a good example of working with a range of partners. The improvement in the coherence of convective systems and the accompanying light rain is noteworthy, since these are long-standing problems for km-scale models. As is often the case, the benefit comes after a careful process of integrating changes to different parts of the model, in this case the CASIM two-moment microphysics scheme, plus the bimodal cloud scheme, interactions with the aerosol parameterisation and tuning of parameters. An important consequece of the new scheme is the ability to unify the tropical and mid-latitude configurations, which will provide benefits for international UM partners. Finally, the speed-ups achieved when the code was optimised were very impressive.

CCP-R2 Although the results are very impressive, the path to operations seems long and complex, with many blocking points, as the experience with CoMorph shows. As in that case (see FS-R4), we recommend an agile process be employed to quickly solve any problems that emerge.

We welcome MOSAC's recommendation, and we are actively reviewing our processes (see response to CCP-R1). Since the MOSAC meeting, the package including CASIM and the bi-modal cloud scheme has been approved to be taken forward in the RAL3 science configuration. This decision was made following an extensive and wide-ranging evaluation across timescales and across the UM partnership. CASIM was a late addition to the package testing following promising results and RAL3 is penciled for a parallel suite shortly after the HPC migration to Gen1. If all goes to plan, this will be an example of a fairly rapid implementation.

<u>Re-Forecasting</u>

The Met Office did a great job in consulting the community and gathering lessons learned from partners who face similar issues. This is essentially a large cost/benefit analysis with significant implications on human and computing resources, and it should therefore be addressed carefully.

Various options were clearly presented. Their arrangement in a sequence with gradually increasing cost is particularly helpful for the decision process. There are obvious low hanging fruits with existing datasets that could be better exploited today, both internally and with the community, without significant cost.

RF-R1 From there, the Met Office may consider pilot studies to quantify the cost/benefit of the option. Throughout the analysis of various options, we stress the importance of planning from the get-go the sustainable aspects of producing, maintaining, updating, and distributing reforecasting data.

We thank MOSAC for raising the important issue of reforecasting. We are currently considering options for reforecasting as part of the use of Gen1 of the new supercomputer. We thank the committee for their specific recommendation on the sustainable aspects and agree that that is a crucial aspect of any approach.

Seamless marine information

MOSAC is happy to see an expansion of impact-based forecast to the marine environment. The various approaches based on lead-time are interesting. MOSAC notes that the skill of the underlying numerical Earth-system and weather-to-climate prediction (NEWP) systems these rely on are important in this context. It is not clear that is considered in the process.

We are grateful for the interest shown by MOSAC. We agree that appropriate consideration (and treatment) of the skill of the underlying data is fundamental to any successful application, acknowledging that 'useful skill' is necessarily dependent on the specific user / decision. It is for this reason the methods presented were all rigorously built on this basis (e.g., selection of thresholds informed by relative economic value analysis and synthesis of long-range trends by the use of weather pattern approaches) – and co-developed with the user – with extensive verification conducted both via offline trials and in live operations. Because of time constraints we did not focus on this aspect within the presentation, but details are available in the papers cited within the MOSAC paper.

As this matures, capturing the many aspects that can impact decisions can help further develop these services. For example, the combination of winds, ocean current, bottom draft, in addition to wave information may lead to a different overall risk. At longer ranges, exploiting dominant weather pattern could also lead to increased accuracy.

We agree that many aspects can impact decisions. The variables presented in these case studies were those identified as being most impactful in terms of both the exposure and decisions of the particular end users with whom they were co-developed. It is, as you say, likely that further developments may need to consider multivariate hazards, but – for the examples presented – these risks were otherwise mitigated (and discounted) by the project engineers with whose systems these data interface, following detailed consultancy review. Since interaction between variables also must be considered outwith those of interest to particular project decisions (i.e., waves impacted by winds, currents, and depth) then these are accounted for through the selection of the appropriate NWP data in which these forcings have been applied.

We have indeed found exploiting the dominant weather pattern to be a useful approach for long-lead time forecasting, and currently have a manuscript describing a permutation of the example presented to MOSAC using this principle (submitted to journal *Meteorol. Appl.*) currently in review.

On the longer, climate time scale, MOSAC recognizes the importance of Sea Level Rise (SLR) and changes in storminess to coastal flooding. Whilst extremal analysis is straightforward, the overall approach isn't clear. The contribution of waves is also missing although they have been known to overtop coastal protection in previous storms. The UK has a lot of expertise in this field.

The analysis presented on long term coastal flood characteristics included only the changes to surge frequencies and time mean sea level rise, as these are the dominant terms for UK coastal flooding impacts and resource for this work was limited. Since the MOSAC meeting we have been

scoping the viability of adding waves into our analysis through WAVEWATCH III simulations, using the same approach as for storm surge, as we prepare the work for publication.

SMI-R1 MOSAC recommends increasing the scientific leadership to this project.

We appreciate the opportunity to present a subset of the diverse projects on marine services to MOSAC. The presentation was designed to highlight the differing drivers behind each project including both “capability-led” and “user requirement-led” projects over different time scales. We note that diverse priorities for model and system developments exist on climate and operational time scales. Through the development of these services, we have been able to explore both the market for these services and also the science required to deliver effective outputs that enable improved decision making. As an organisation we work across the Science, Programmes and Markets directorates, and with our external partners, to manage the competing priorities across the organisation.

SMI-R2 Over the past 2 years there have been several mentions of shelf/coastal R&D areas. It is not clear how much coordination exist between these different efforts. Additional information on R&D and operationalisation plans, including for coupled systems would be welcome.

Although the NWP model development and applied science teams are hosted within different directorates, there is frequent cross-office working and collaboration between them. Such coordination can always be increased, however, with a key initiative in this regard being the recent establishment of the new Marine Assurance Group in March 2022. This group is chaired by the Head of Ocean Forecasting Research & Development, but has representation from key users from model development, applied science, Services, and Markets – providing a bimonthly review of activities and impacts by the key stakeholders throughout the end-to-end delivery chain. We acknowledge the request for additional information on R&D and operationalisation plans. This could be a suitable topic for future MOSAC meetings.