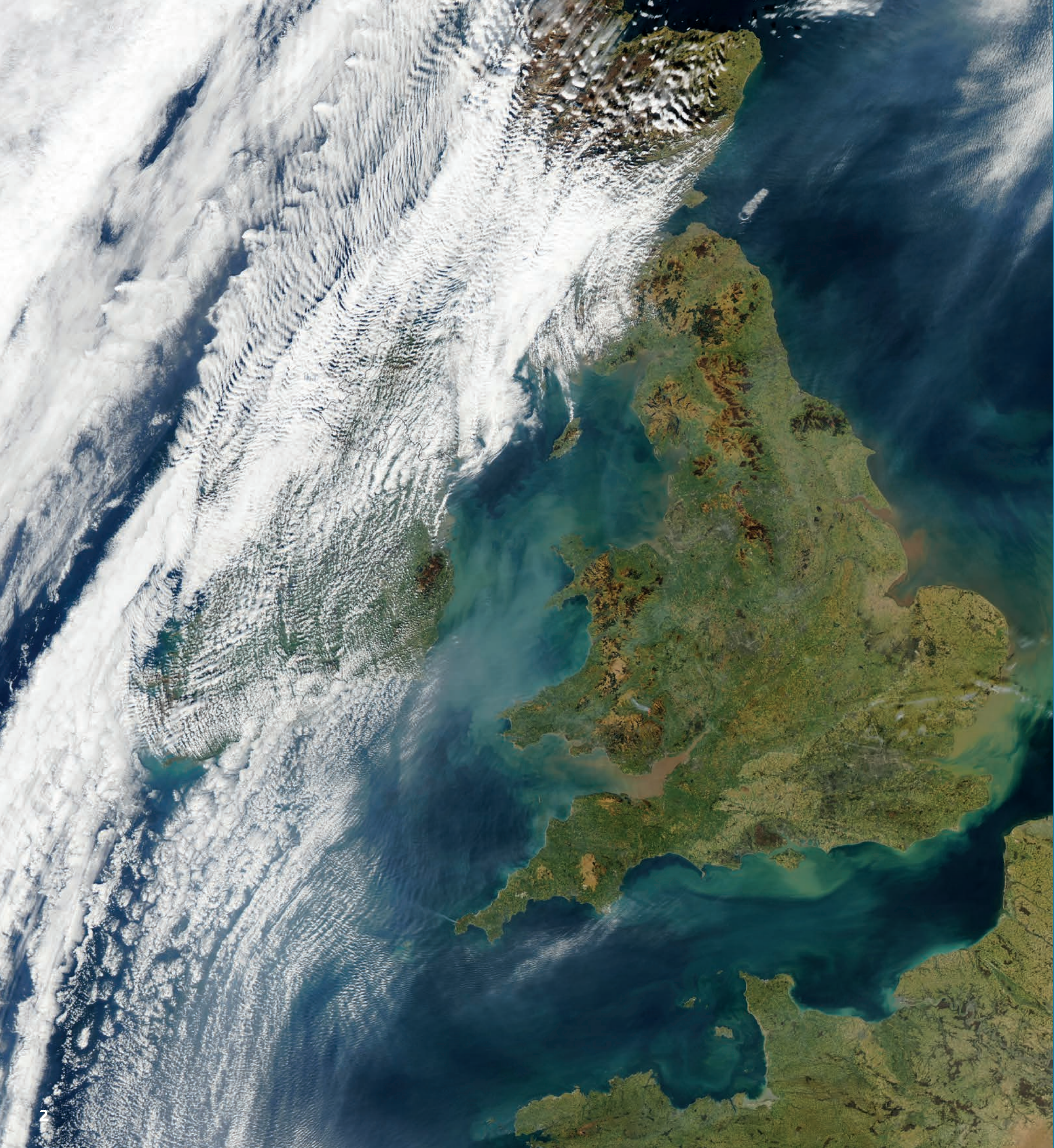
Met Office

Weather and climate science and services in a changing world

Research and Innovation Strategy | April 2020 | v.1



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Foreword

Weather and climate science and services have never been more important. The risks from high-impact weather events, and how they might change in our changing climate, rank high in many national and corporate risk registers. Better forecasts, with longer lead times, tailored to impacts all help to minimise the damage.

At the same time, technology is changing at an ever-increasing pace: novel supercomputers promise enormous power if harnessed effectively; public sector cloud-based technology offers profoundly new ways of analysing data; and data sciences and artificial intelligence are already leading to huge new insights.

This Met Office Research and Innovation Strategy brings together three strands: the new opportunities enabled by new weather and climate science; the future technologies that will radically increase our ability to compute forecasts, analyse the data and serve information to our sponsors; and the processing and visualisation of this information to produce guidance. In this way this R&I Strategy provides our ambitions and priorities to support the central Met Office strategic anchor, namely our exceptional science, technology and operations.

We have bold plans to re-engineer the computer codes we use to simulate weather and climate to make them fit for purpose for the next generations of supercomputers. We are eager to use the new data sciences of machine learning and artificial intelligence to complement these simulation tools, to produce the best possible forecast information. Furthermore, we shall push on from forecasting weather hazards to forecasting the impacts of these hazards so that decisions are made on the best evidence.

This is an ambitious agenda that goes far beyond the traditional disciplines of weather and climate science and technology. We recognise that to be truly innovative and to deliver on this ambitious agenda, we shall need to forge innovative partnerships across traditional discipline boundaries.

Here we describe the motivation for the Research & Innovation Strategy and introduce our response. Each of the nine Research & Innovation themes and the three cross-cutting themes have more detailed plans that will be circulated soon.

This R&I strategy provides an exciting glimpse into what might be possible, with the focus and drive I see at the Met Office, it can become reality!

PROFESSOR STEPHEN BELCHER
CHIEF SCIENTIST

Introduction

Predicting our weather and climate, and their impacts has become one of the most important areas of scientific and technical endeavour. We have seen significant advances in forecasting skill. But there is a constant need for improvement as society drives for greater efficiency and resilience. There is also now an increased and urgent need to understand our rapidly changing climate and the effect this will have on each and every one of us. The Met Office therefore exists to help you make better decisions to stay safe and thrive.

The vision of the Met Office is to be recognised as global leaders in weather, climate science and services in our changing world. Meanwhile our world changes at increasing pace, from technological innovation, to the need for clean growth, to the change in the climate itself. The Met Office strategy to deliver this vision is centred around three strategic anchors: Excellent people and culture; exceptional science, technology and operations; and extraordinary impact and benefit.

These extraordinary impacts and benefits are delivered by the services Met Office provides to government, business and citizens, which then drives research and innovation in our exceptional science, technology and operations. All this is only possible because of the excellent people and culture, and our rich network of structured partnerships with exceptional organisations across the world.

The Met Office has pioneered the concept of seamless science from weather forecasts through to climate change projections, and provides services from global prediction to forecasts for individuals, and the research and innovation programme ranges from deep scientific research and technical innovation to operational services. This Research and Innovation Strategy builds on our rich past, responds to the challenges posed by a changing world and sets out the priorities needed to develop our central anchor: exceptional science, technology and operations, over the next 10 years.

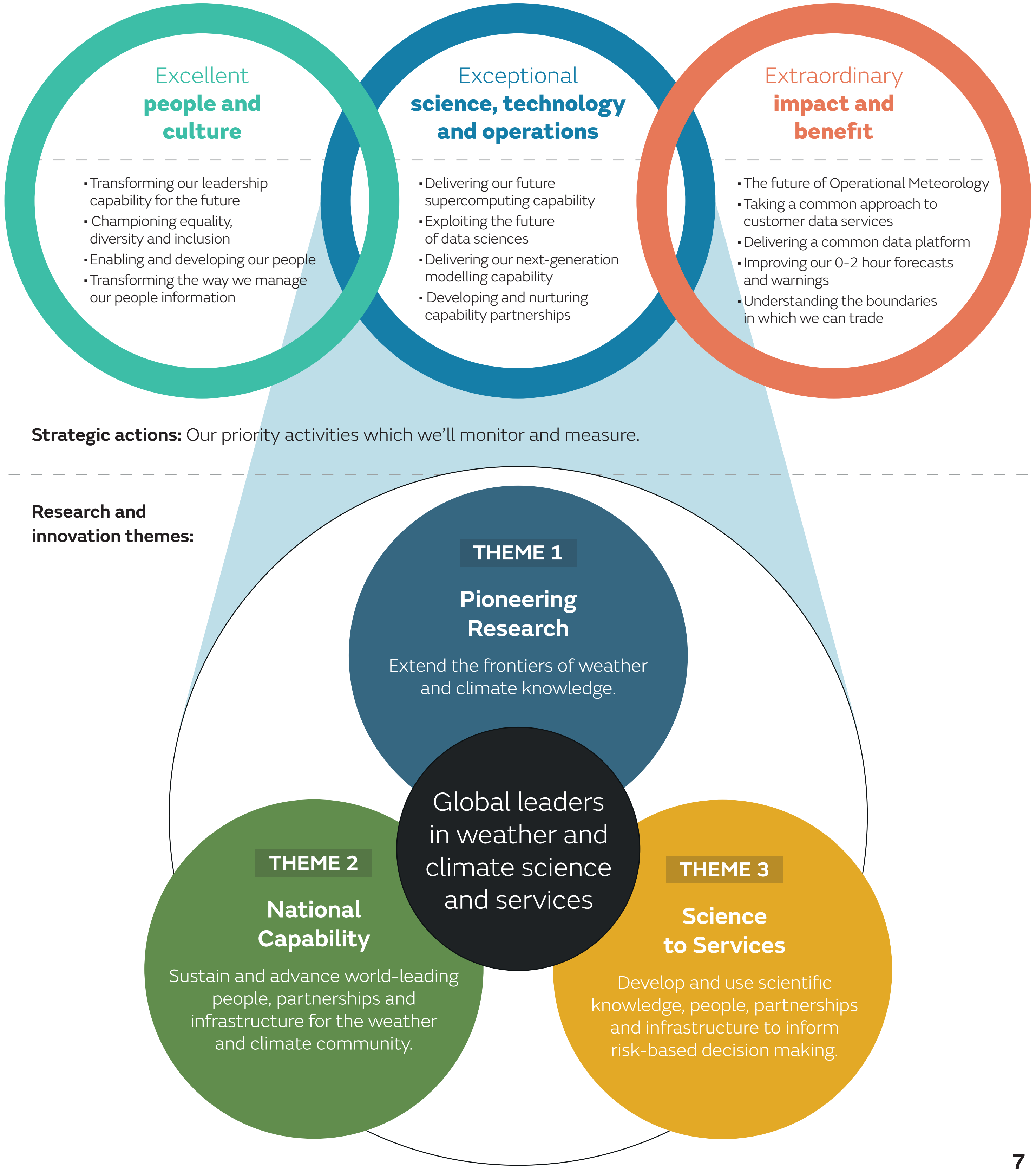
Our vision: What we want to achieve by 2024

Recognised as global leaders in weather and climate science and services in our changing world

Our purpose: Why we exist

Helping you make better decisions to **stay safe and thrive**

Strategic anchors: These are the areas we will focus on. The three areas overlap and complement each other.



Weather and climate science and services in our changing world

As our ability to better understand and predict future weather and climate develops, so too do the expectations of our customers and stakeholders. These evolving demands, together with the opportunities provided by new technology, provide the drivers for this Research and Innovation Strategy.

High-impact weather

As citizens, we expect safe housing and resilient provision of food, water and energy, and we increasingly rely on efficient transport systems and global telecommunications. All are vulnerable to high-impact weather: communities can be devastated by flooding, heavy rainfall and strong winds, crops can be damaged by intense rainfall or drought, aircraft can be grounded by thick fog, and, beyond conventional weather, critical infrastructure can be sensitive to space weather. Damage can often be reduced by providing earlier warnings, requiring longer range forecasts of the high-impact events. Increasingly, probability-based forecasts allow risks to be progressively managed in the period leading up to a significant weather event. Furthermore, there is a demand to not just predict the weather, but also the impacts of that weather. There is a growing need for impact-based forecasts.

In addition to forecasting weather hazards, there is also an increased demand for personalised forecasts as the growth of global connectivity and smart technology allows more people to access and use forecasts in their day-to-day lives. This demand is driving a requirement for ever more accurate, localised weather forecasts. These new smart devices also provide opportunities for a massive increase in measurements of the weather to inform forecasts, which could help personalise and localise forecasts.

When a vulnerable community is affected by high-impact weather the emergency response teams require accurate assessment of the current weather conditions and how they may change in the near future. This situational awareness needs to be rapidly updated during the emergency and then continually updated through the course of the recovery, which can last for weeks, months or even years.

Finally, we need to make our communities and infrastructure more resilient to high impact weather. To do so requires assessment of worst-case scenarios: how bad could it be? The wet winter of 2013/14 brought widespread flooding to the UK. Is this the wettest winter season that we should expect in a present-day climate? The risks from compound events could be even greater. For example, the weather systems that bring heavy rain during winter, which can cause flooding, often also contain gale-force winds, which can lead to coastal storm surges; or the passage of one high-impact event can heighten the vulnerability of communities and infrastructure to a subsequent event.

To meet these needs requires substantial scientific development and technical innovation. Weather forecasts need to become more accurate and the lead-time needs to be longer. Increasingly we need impact-based forecasts for an increasing range of impacts. We require the ability to provide situational awareness during a rapidly evolving emergency. We also need assessments of worst-case scenarios of high-impact weather events, including the possibility of compound events, when multiple weather events and other emergencies strike in a short time period.

Changing climate, changing hazards

The climate is changing. Global mean temperatures have risen by more than 1°C since pre-industrial times, sea levels have risen, and ice sheets and glaciers are retreating. The observed magnitude and pattern of these changes means that there is very strong scientific evidence that these climate changes are due to the increased levels of greenhouse gases in the atmosphere.

The 2015 Paris Agreement set out a global commitment to keep warming below 1.5°C and the UK has set a target to reach net zero emissions by 2050. To meet these commitments requires a scientifically robust understanding and management of national and global carbon budgets to provide pathways to stabilise the climate at a safe level. It also requires monitoring the climate to chart progress towards the ambitious targets, and to check for unexpected changes, tipping points and potentially irreversible changes to our environment.

As the climate changes so too do the high-impact weather events we need to prepare for. When combined with a growing population, living increasingly in mega-cities, our exposure to the impacts of weather hazards is changing, and in many cases increasing. Therefore, there is a need to assess how the impact of extreme weather events will shift within our changing climate. This assessment needs to have a global view: modern economies are dependent on complex global supply chains that mean that high-impact weather events have complex implications across the world; some studies point to the risks of conflict driven by pressures on resources from climate change. Furthermore, many developing countries are particularly vulnerable to weather and climate hazards and resilience could be increased through partnerships to enhance capability and effectiveness.

These are significant scientific and technical challenges that will require better climate science, better climate models and better ways to communicate and enable decision making. But, crucially, they also require a new multidisciplinary approach. For example, combining climate scientists and operational meteorologists, with engineers, economists and behavioural scientists to integrate climate information and knowledge with other sources of information to build solutions. This will require new networks and partnerships that extend beyond the Met Office's traditional relationships.

National Security and Emergency Response

UK Security and Defence activities are dependent upon accurate weather forecasts to ensure the safety and security of personnel and equipment. These are provided by the Met Office through a suite of data feeds, tactical decision aids and by specialised operational meteorologists. Environmental conditions have an impact on many levels of military operations, ranging from real-time decision making to the implications of climate change for future platforms. The UK has invested in technology and infrastructure to provide strategic advantage, much of which is weather sensitive. Accurate weather forecasts for key global locations, alongside reliable advice and guidance, are vital to enable its exploitation. Increased precision at global and regional scales of the impacts of climate change will help inform UK defence strategy for safer and more effective military operations around the globe now and into the future.

Alongside Security and Defence, the UK National Risk Register identifies a broad range of high impact risks to the UK, ranging from flu epidemics, through flooding, to threats from cyber security. Of the 20 risks currently identified, 12 are either directly related to, or have a strong dependence on weather and climate. These risks encompass periods of exceptionally hot or cold weather, and periods of exceptionally wet or dry weather. They also encompass the transport and dispersion of harmful chemicals or pollutants into the atmosphere or water systems, and the threats to infrastructure from space weather events.

The Met Office has a national responsibility to assess the likelihood of these threats, and how they change in the changing climate, and to provide an operational response in the event of an emergency. New science and innovation is needed to ensure we identify and respond to these and new risks, and to ensure the efficiency and robustness of the emergency response capabilities.

Clean growth and innovation

Within the context of a changing climate, growing technological advances and a changing social consciousness, there is an increasing focus on clean growth, as reflected in the UK Industrial Strategy. This revolution will require a raft of new environmental prediction services.

Increasingly, new industrial and societal processes are designed, monitored and optimised using digital twins: a digital model of the process as a system. Environmental factors often play a role. For example, high-impact weather is a factor in the reliability of supply chains and cold or hot weather is a factor in the demand for heating and cooling in energy systems design. The challenge of a move to net zero carbon emissions will require systems modelling of this nature, in addition to understanding of the natural carbon budget. Integration of weather and climate data and modelling into these digital twins will require innovative technological and scientific thinking.

The increased commitment to net zero carbon emissions is resulting in new innovations in renewable energy and transport systems. This new infrastructure will be heavily reliant on weather conditions for operations. For example, wind and wave power rely directly on the weather to generate power. And connected autonomous vehicles, such as driverless cars, rely on weather-sensitive sensors and communications networks; they also need to respond to different driving conditions, brought on, for example, by fog or heavy rain. There is a growing need for new types of observations and forecasts to ensure the efficiency of new infrastructure.

Poor air quality is known to affect human health. In the UK there is a drive to develop technology and policy to improve air quality, particularly in cities. Worldwide, rapidly developing economies have sometimes come at the price of very poor air quality. As the UK's national meteorological service, the Met Office has a responsibility to enable scientific analysis across the whole chain, from pollutant emission through to airborne dispersion, exposure and health impacts.

Internationally, the clean growth agenda is being promoted through the Sustainable Development Goals, and the UK has a vital role to play in delivering these targets. Clean energy, resilient infrastructure, food security and climate mitigation are all key aspects of the Sustainable Development Goals and are all heavily linked to weather and climate. The Met Office will be able to support this agenda by building capacity overseas through training, infrastructure, communications and emergency assistance.

The revolution of clean growth therefore presents a need for new services from the weather and climate community. These new services will require scientific development and technical innovation, and, of course, multi-disciplinary teams to deliver services.

New technology, new science

Technological advances are providing huge opportunities for innovation in weather and climate science and services. Artificial intelligence and machine learning are expected to revolutionise the way the world operates. When paired with next-generation supercomputer capabilities and exploitation of public cloud technologies we will be able to push the limits of weather and climate prediction more than ever before, combining the disciplines of simulation and emulation to increase the efficiency and accuracy of weather and climate prediction. Furthermore, data analytics provides huge opportunities to add value to weather and climate data to produce new services. But at the same time, these new technologies will produce data at such huge volumes that we shall need radical new ways of moving data, post processing model output, and serving the data services to users.

Taking advantage of these new capabilities will require new skills, new technology, new science and modelling techniques and new partnerships. There will also be an increased requirement for multi-disciplinary approaches to address the challenges laid out above as weather and climate science and operations interact with social science, data science, engineering and technology. Again, this will increasingly mean the Met Office's in-house specialist expertise and pioneering partnerships will be of utmost importance if we are to deliver on the goals of this Strategy, support the Met Office's capabilities and be prepared for the future.

Our vision

To achieve our vision to be recognised as global leaders in weather and climate science and services in a changing world we cannot stand still, we shall need to continually extend our science and services through research and innovation. Our approach is to build on the unique breadth of the science, operations and technology within the Met Office: seamless from weather forecasts right through to climate change, from global prediction to forecasts for individuals, and from deep scientific research and technical innovation to operational services.

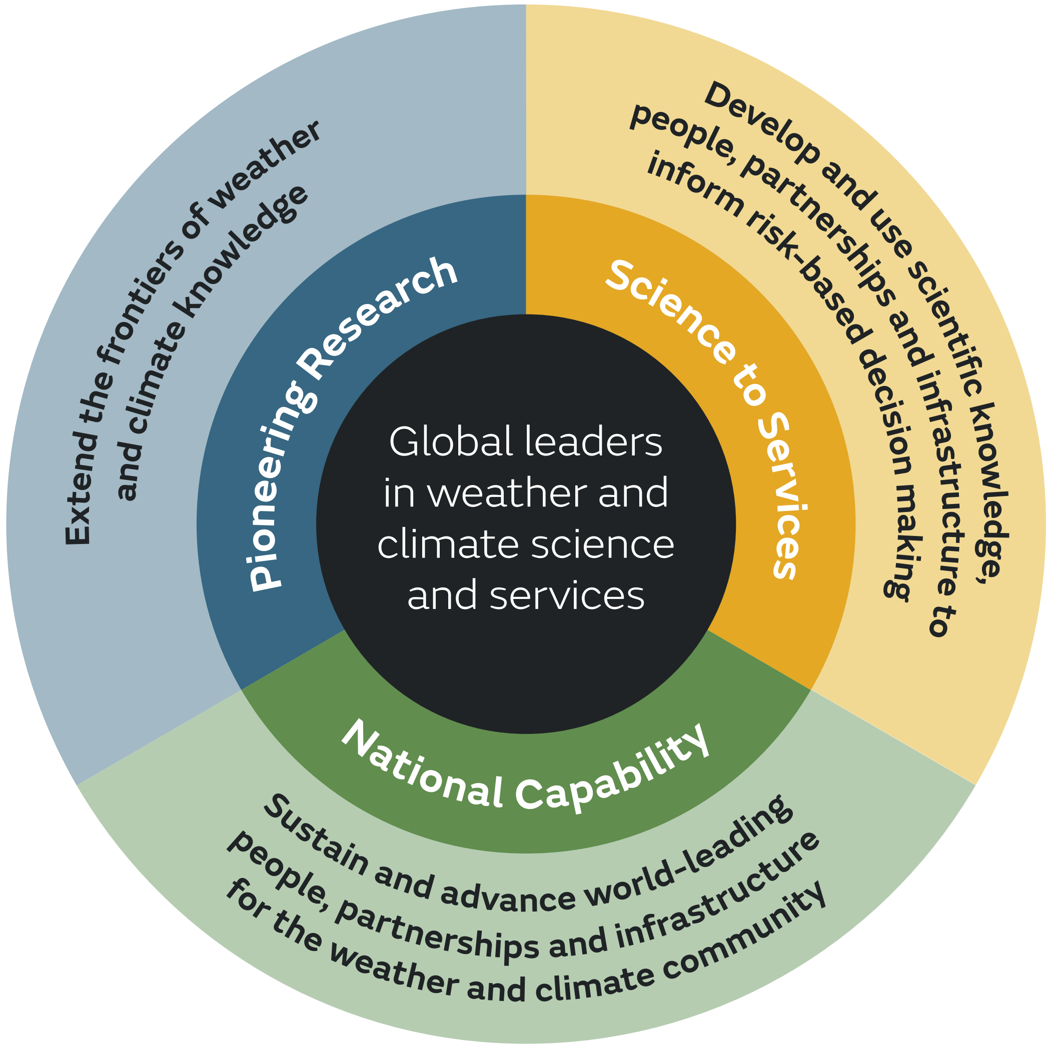
Such ambitious goals require research and innovation in three core activities:

Science to Services
The way we develop and use scientific knowledge and services to inform risk-based decision making.

Pioneering Research
The fundamental research we do to extend the frontiers of weather and climate knowledge.

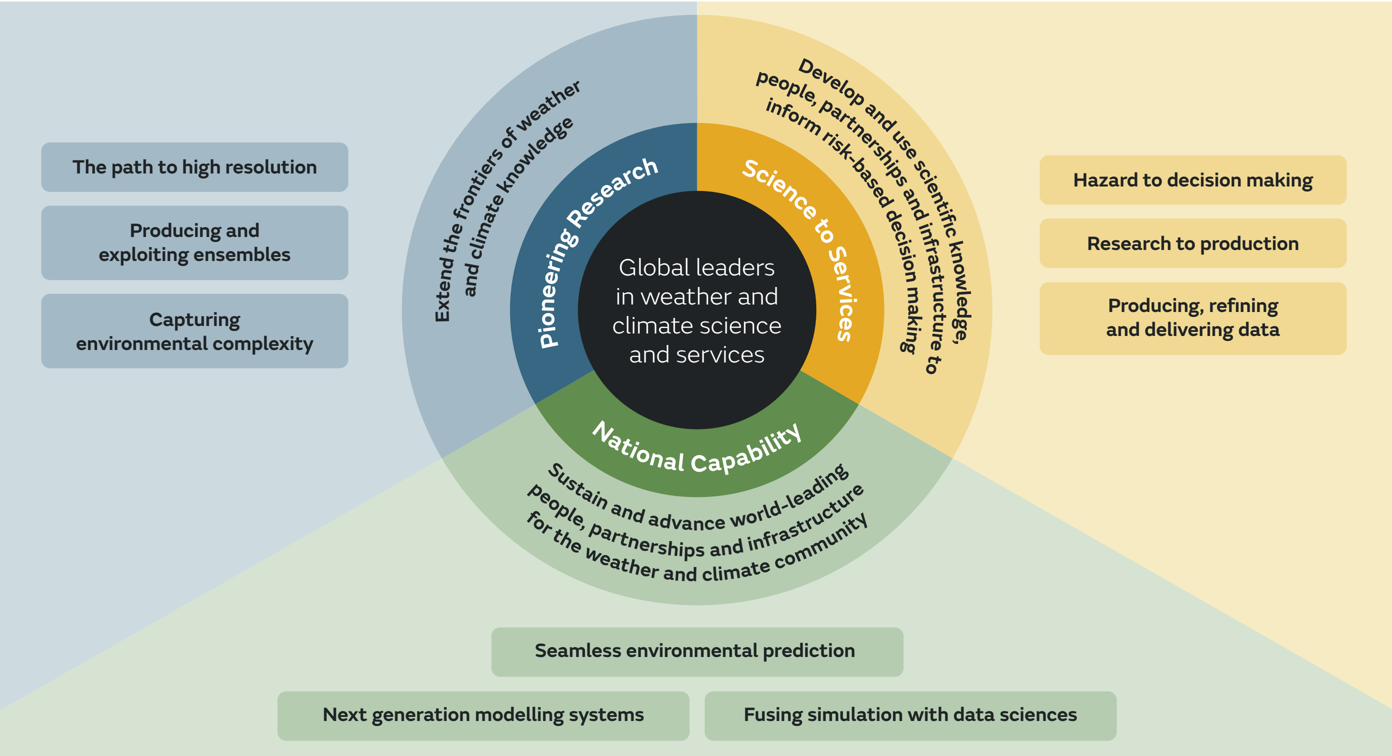
National Capability
The people, partnerships and infrastructure that enables the weather and climate community to meet UK and global strategic needs.

Development of new and improved services is the reason we have research and innovation within the Met Office. But new and improved services require pioneering research. And the Met Office has a responsibility to nurture and develop national capability for weather and climate science and services, which then enables the broader UK and international community.



Research and innovation themes

Across these three core activities we have designed nine Research and Innovation Themes to respond to our top customer and stakeholder-driven research priorities. Some continue to build on areas of internationally-recognised excellence, such as building on our seamless science approach to environmental prediction and pushing observations and modelling towards higher resolution to better represent high-impact weather hazards. Others respond to changes in technology, such as preparing our whole modelling systems for the next generation of supercomputers. Others are new areas. For example, developing the new generation of impact-based weather and climate services will require a translation of the weather hazards into risks and impacts, so that informed decisions can be made. New innovative data processing and platforms will be required to make this possible. And the broad range of new techniques in data sciences offer exciting new opportunities, when harnessed with our simulation tools.



These nine research and innovation themes are:

Science for Services

Hazard to decision making

Expand and improve our services for stakeholders' risk-based decision-making by working with users, social scientists, behavioural scientists, financial impact experts and engineers to gain an increased understanding of the impacts of hazards and to develop better impact-based services.

Research to Production

Pull through developments in weather and climate research to improve our forecast systems, tailored to services in the forecasting timescales of primary interest to the Met Office and its customers.

Producing, Refining and Delivering Data

Develop the Met Office supercomputing estate for operations and research, establish the technology and science needed to move, store and process our data, and design a flexible post-processing framework to turn predictions and observations into customer products.

Pioneering Research

The path to high resolution

In order to better predict hazards and extremes, develop the next generation of very high resolution global and regional environmental prediction systems, based on global convection-permitting atmosphere models coupled to eddy-resolving ocean models and eddy-permitting regional atmosphere models coupled to estuary-resolving shelf-seas models.

Producing and exploiting ensembles

In order to include forecasts of uncertainty at the heart of our endeavour, develop ensemble-based systems and exploit them for prediction across timescales, while developing new and novel uses of ensemble information for improved understanding of weather and climate.

Capturing environmental complexity

In order to pioneer new and improved impact-based forecast services and advice on global climate change mitigation, extend our environmental prediction capability with a focus on cities, air quality, the water cycle, and carbon and nitrogen cycles.

National Capability

Seamless Environmental Prediction

Further develop our world-leading seamless environmental prediction capability, whereby a single model family is used in conjunction with observations and theory, to quantify weather hazards in the past, in present day climate and into the future across weather and climate timescales.

Next generation modelling systems

Revolutionise the Met Office's complete weather and climate research and operational simulation systems so that the Met Office and its partners are ready to fully exploit future generations of supercomputer.

Fusing simulation with data sciences

Use new and evolving data science methods such as artificial intelligence and machine learning and advanced data assimilation in order to remain at the cutting edge of weather and climate prediction and impact-based services.

Along with these Research and Innovation themes there are three cross-cutting themes which will impact all areas of our science, technology and operations: People, Practices and Partnerships. These are critical to the success of each of the Research and Innovation themes.

Cross cutting themes: an overview

The ambition and vision within this strategy can only be realised with three cross-cutting themes which enable all areas of our science, technology and operations, namely People, Practices and Partnerships.

People

Talented and driven people will be at the heart of delivering this strategy. And so it will be essential to attract, retain and develop diverse talent across science, technology and operations at a time when the nature of the workplace, and expectations of staff, are changing. With this in mind, our People vision is to lead and invest in our people and culture to make the Met Office a great place to a work. And the Met Office People Strategy is a long-term plan that ensures we deliver on our people vision and keep our commitment to making the Met Office a great place to work.

Partnerships

This strategy demands an increase in the range of skills and expertise we shall need to bring to bear, and so working in partnership will become more important than ever before. We shall develop and nurture our existing partnerships, within the weather and climate domain, in universities, national research centres, ECMWF and other national met services. New partnerships and new networks will be needed with whole new ranges of scientists and technologists to rise to the expanding challenges. And finally, our development of partnerships will need to recognise that increasingly research and innovation in weather and climate science and services take place in both the public and the private sectors.

Practices

People and partnerships need to be supported through the right working practices, be it the way we organise our working lives, the way we organise and deploy our teams, or the software tools we use. We shall need to embrace new approaches, and ensure staff are trained in best practice in computing, coding, observation and research tools. In this rapidly changing environment, change will be ever present, and we shall need to ensure these changes are managed well.

Hazard to decision making

The Met Office's world-leading science capabilities for hazard forecasting are vital for providing businesses, governments and local authorities with the information they need to protect vulnerable communities and infrastructure during adverse weather. As well as the continual improvement of our forecasts of weather and climate hazards through the planned advances in operational prediction, we will expand our knowledge of the impacts of these hazards for our customers and their decision-making processes. Developing an in-depth knowledge of our customers' vulnerabilities and exposure to these hazards and how they make decisions will allow us to provide more detailed and accessible advice on how weather and climate events will impact their operations. This increased knowledge will enable local, national and international authorities and businesses to better preserve life and assets and support delivery of government's ambition to reduce risk of harm from environmental hazards.

Goal

Expand and improve our services for stakeholders' risk-based decision-making by working with users, social scientists, behavioural scientists, financial impact experts and engineers to gain an increased understanding of the impacts of hazards and to develop better impact-based services.

To achieve this vision by 2030 we aim to:

1. Consolidate our position in emergency response to atmospheric dispersion events and space weather events by continuous improvement of the modelling and observational systems.
2. Develop demonstrators and services relating to climate hazards to impact prediction in the UK in areas such as urban, marine and health.
3. Deliver sustainable and growing hazard to decision making services to external stakeholders. Services will cover weather and climate timescales and will be provided in partnership with external organisations who contribute specialist skill sets.
4. Build a community of external partner organisations including industry, government and academia, working with the Met Office to gain skills and understanding in the risks of impacts to enable better decision making.
5. Use the best ensemble, post-processing and data science techniques to create new risk-based prediction services for a variety of hazards.

The impact areas we will focus on include:

- Wind, snow, ice, surface flooding and heat stress
- Landslides, coastal erosion and wildfire
- Inshore marine (including fisheries)
- Urban meteorology and climate
- Food and water security (including drought)
- Dispersion of hazardous chemicals and radioactive materials
- Space weather
- Multiple hazard impacts

Case studies

Defence

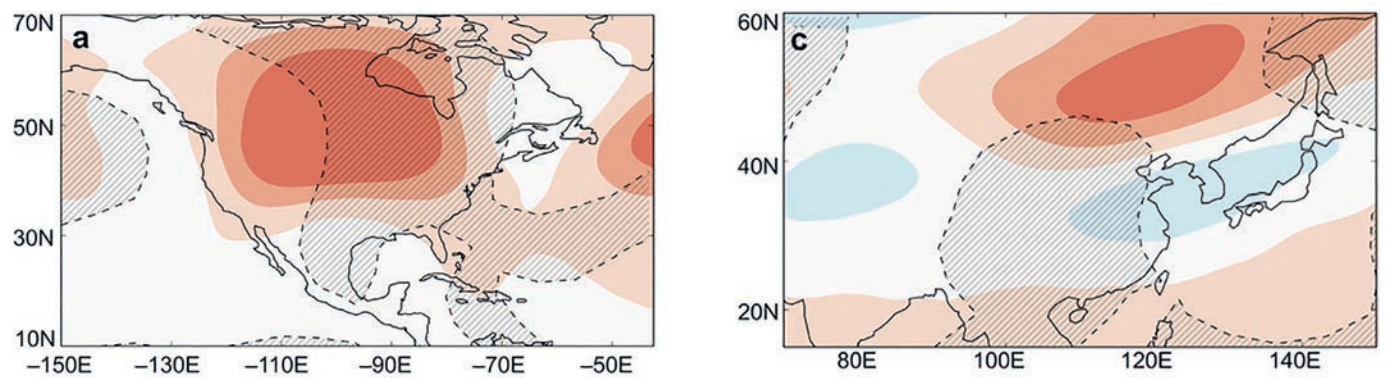
The opening of summer-time Arctic shipping routes brings potential for conflict and the requirement that the Royal Navy can operate safely in the harsh Arctic environment. Meteorological and oceanographic hazards include: the physical presence of sea-ice, icing of surfaces from sea-spray and poor visibility; complex radar, communications and even optical propagation environments that can compromise sensor performance; and complex underwater acoustic detection environments. All of these provide opportunities for significant scientific research and development to improve understanding.

Royal Navy submarine HMS Trenchant after it had broken through the metre-thick ice of the Arctic Ocean to join two US boats during Ice Exercise 2018 in March of this year. Courtesy of MoD.

The interplay between these hazards and many other non-environmental hazards will play an important role in real-time decisions on where to position a platform, planning of transit routes, incoming-threat assessments and deployment of countermeasures. Good decision-making will ensure that the risk of significant damage to the platform (potentially including complete loss of a ship and its crew), is minimised, and UK interests are protected. The understanding of the full risk system, which again includes non-meteorological factors, and how it is changing will also inform long-term strategic investment decisions from MoD for equipment acquisitions and the development of new technologies. The Met Office will work in partnership with key defence stakeholders across the UK and internationally to realise this risk minimisation.

Risks to global food supplies

With a growing global population and changing climate, food security will be an increasingly important challenge. This is exacerbated by the fact that large amounts of food production are often concentrated in small geographic areas and are susceptible to climate extremes such as severe water stress which could have disproportionally large impacts on global food supplies. Where there are limited agricultural and climate observations it is difficult to predict the probability of extreme events affecting crops, making planning difficult. However, through the UNSEEN method (UNprecedented Simulated Extremes using ENsembles), the risk can be calculated through improved sampling of natural variability despite limited observational data. Simulations can be used to identify unprecedented climatic patterns that threaten crops (below) and allow quantification of the risk of shocks to food supplies brought by the combined effects of climate change and natural variability, thereby aiding attempts to ensure food security both nationally and internationally.



Plausible, but unprecedented June-July-August conditions associated with national-scale severe water stress events which would threaten maize crops over North America and Asia. The colour shading shows the 200 hPa geopotential height anomalies. Red areas indicate areas of higher than average values –these conditions are associated with dry conditions which would severely impact maize yields.

Research to production

Over the next decade, there will be a continuing trend towards impact-based environmental prediction, using atmospheric, land, marine and hydrological observations and simulations for coupled models on both a local and global scale. Our pioneering research into resolution, ensembles, complexity and hazards will be translated into world-class modelling and observations systems. We need to maximise the value of these systems to operational meteorologists so that they can provide the best advice to our customers. In addition, the quality of our automated products must remain world-leading in a competitive market. To achieve these goals, we must ensure that the tools, techniques and products available for downstream users are fit for the future. This will require new ways of working between research and operations and exploitation of new technology.

With the increased complexity of NWP and climate modelling, the transition of research into operations becomes increasingly costly and challenging. At the same time the requirement for climate models is changing: the scientific evidence has established that the climate is changing and that the majority of warming in the 20th century is due to greenhouse gas emissions. Consequently, the operational requirements of climate models are moving from the qualitative to the quantitative; the Paris agreement established stringent targets and our progress against these targets require quantitative assessment.

Goal

Pull through developments in weather and climate research to improve our forecast systems, tailored to services in the forecasting timescales of primary interest to the Met Office and its customers.

To achieve this vision by 2030 we aim to:

1. Develop objective methods to determine the optimal balance between resolution, ensemble size and complexity for the range of operational forecast systems.
2. Develop and implement a consolidated, comprehensive national/local-scale nowcasting capability. We will combine novel observations, advanced data blending and temporal integration from minutes out to 1-2 hours ahead for the analysis and very short-range prediction of routine and hazardous UK weather.
3. The development of a coupled, ensemble-based, relocatable km-scale local environmental prediction capability focussed on routine and hazardous weather and its impacts out to 2 days and beyond.
4. Achieve a step-change in UK km-scale NWP performance through enhanced weather and climate research focussed on the representation and prediction of the primary routine and hazardous UK weather parameters (fog, precipitation, surface temperatures/winds and cloud), and advanced post-processing and verification techniques.
5. Implement coupled, ensemble-based, 5 km-scale global environmental prediction focussed on routine and hazardous weather out to 7 days and beyond. Use well-designed, world-leading, robust, reliable, multi-decadal climate projection systems that encompass uncertainty for delivering risk-based national UK and global projections. Support International Policy agreements and explore cutting-edge research.
6. Deliver reliable climate model information at regional scales and on extremes for climate impacts.
7. Design production climate models that are fit for the purpose for assessing greenhouse gas budgets, climate warming targets and future climate hazards for adaptation.

We will focus on the following priorities:

- UK national/local nowcasting in the 0-2 hour range
- UK km and sub-km scale national/local environmental prediction on the 1 hour to 2 day range
- Global environmental prediction out to day 7
- Sub-seasonal forecasting out to a month ahead, through partnership with ECMWF
- Seasonal forecasting for the 2-4 month range
- Near term climate prediction for the 1-5 year range
- Global/regional climate change projections on multi-decadal to centennial timescales
- Cross-disciplinary working to enhance pull through to operations and prioritise development

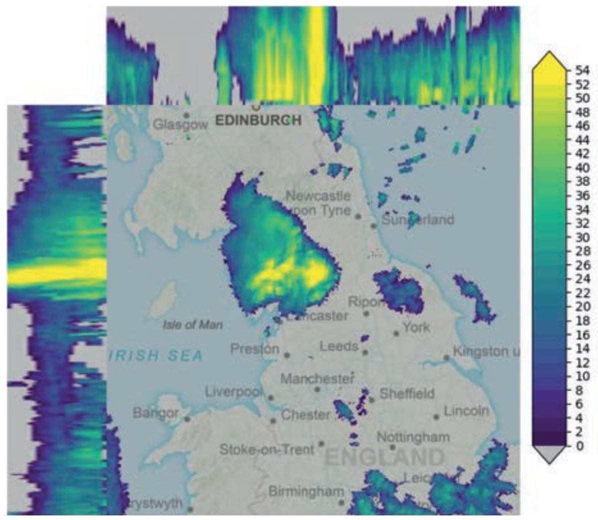
8. Ensure that the technical and scientific infrastructure, including novel data platforms and visualisation systems, is in place to allow model and observational data to be fully exploited in downstream applications. Develop new approaches in operations to optimally utilise these data.
9. Mature the process for taking research NWP, seasonal prediction and climate services into operations, and maintain a cross-disciplinary team from Science, Technology, Operations and the wider business to set the agenda for future improvements.
10. Use cognitive science to understand and improve decision making in operational forecasting.
11. Extract the maximum benefit from our core observing networks through higher temporal sampling and utilisation of the full capability (e.g. three-dimensional weather radar data) and supplement these high quality observations with crowd sourced data and other opportunistic data sources to provide the higher spatial and temporal resolutions that are required.

Case studies

Nowcasting

Nowcasting is the diagnosis of current weather and forecasting on a very short-term period of up to 2 hours ahead. Accurate nowcasting is important for situational awareness during periods of high-impact weather. The availability of new observations, such as advanced weather radar and crowd sourced measurements, and novel data science approaches such as machine learning, mean that there are now significant opportunities to advance our nowcasting approaches and systems.

Radar imagery and accompanying photo of cloud-to-ground lightning strikes over Exeter, Devon, late in the evening on 23 July 2019. Photo taken by Matt Clark, Met Office.



Three-dimensional radar observations allow the horizontal location and depth of convective cells to be easily identified, enabling better advice and warnings during a severe weather event. This example imagery shows transects through a 3D cube of gridded radar reflectivity (dBZ) on 25 July 2019. The plan view shows the maximum reflectivity in the vertical column above each horizontal location. The side panels show vertical cross sections of maximum reflectivity along (left) north-south and (top) east-west planes. In this case, the feature of interest is a supercell, with a cloud top above 12 km. This caused wind damage near Hawes and large hail was observed in Northumberland.

Producing, refining and delivering data

Maximising the impact of our science for users and stakeholders will only be possible with enhanced capacity in supercomputing, data archiving and platforms for data processing and analysis.

Our current approach to creating, analysing and disseminating our data is the result of 50 years of incremental scientific and technological advance with little co-ordinated reform or consolidation. As technology advances and the scale of the challenge increases, (driven largely by increasing data volumes), new infrastructures and processing chains have been created in isolation to serve specific customers or customer groupings. This has created many challenges. For example, our products are numerous and complex, meaning they are difficult to re-use, adapt or change.

As the power of computers and observing systems increases, so does the volume of data. There is a need to ensure that the technical capabilities are in place to move, store, process and access the data. A new probabilistic post-processing framework will be developed and implemented, simplifying the production chain from observations and model output to customer products. We will create the ecosystem and interfaces to make our data discoverable and accessible to both internal and external users and customers, enabling development of novel products and services.

Meanwhile, our services and solutions will become more consolidated, efficient and cost-effective and will better reflect those used widely in industry.

Goal

To establish the technical capabilities required to produce data and make it accessible and discoverable, and to develop frameworks and scientific methods to process the data into the information required for scientific analysis and customer applications.

To achieve this vision by 2030 we aim to:

1. Access supercomputing, data archives and analysis platforms necessary for our world-leading research and operations.
2. Establish new post-processing frameworks and scientific methods and platforms to deliver products for the public and all customers and stakeholders who access our weather and climate predictions.
3. Develop the technical capability (including data platforms and visualisation systems) required to manage, process and make available the expected huge increases in data volumes.
4. Organise existing infrastructure initiatives so that they are scientifically, meteorologically, programmatically and technically aligned.

Case study

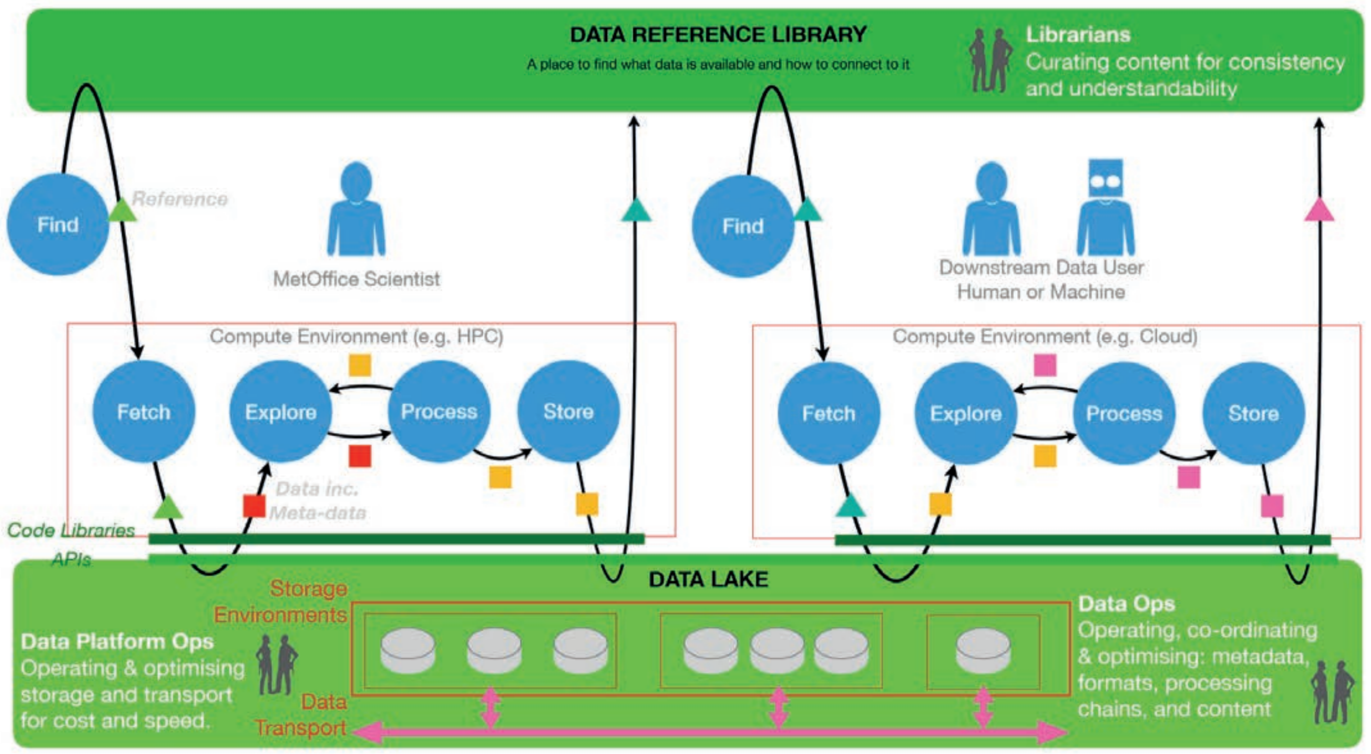
Data platforms

As simulation becomes more sophisticated as a result of developing science and technology, 'data as a product' becomes much more prevalent and important. Increasingly, decisions are made by our customers and stakeholders based on the analysis of data by a machine rather than by visualisation of it by a human. Traditionally, the use of weather and climate data in this manner was typically only undertaken by a domain-expert scientist or meteorologist. As machine consumption of data becomes more common, the approaches to post-processing, representation of uncertainty, quality and detail of metadata all become more important.

At the same time, simulation data is becoming so verbose, it can be expensive to distribute. Driven by these factors, data services today tend to be limited in terms of fidelity and detail such that they can be effectively moved and consumed by users. In order to maximise the degree to which our data can support decision-making we will deliver a new platform to post-process, package and transfer data in a way that maximises the information required to support decision making.

We therefore need to create the ecosystem and interfaces for the discovery, access to and processing of environmental data. These data platforms must:

- Create value for end users through services operated by the Met Office and third parties using environmental data provisioned from the platform, including new data formats and higher volume data;
- Provide discoverable and shareable environmental data and processing through a common platform on a self-service basis with minimal configuration;
- Support libraries, tools, and services for internal and external parties to participate in a secure, reliable, observable, scalable, and affordable platform;
- Be well managed – enabling monitoring, capacity planning, cost allocation and usage governance; and
- Continue to evolve to support on-going developments in new science, technologies and capabilities



A schematic representation of a data platform, illustrating storage of environmental datasets within a "data lake" and the ability of both Met Office scientists and external users (human and machine) to access and process these data.

The path to high resolution

The Met Office's world-leading seamless weather and climate modelling is central to what we do. Numerical simulations are our primary tool for exploring the behaviour of the coupled atmosphere-ocean system. Using these simulations alongside observations allows us to better understand the weather and climate system and this is vital in order to improve our ability to predict high-impact weather events and the effects of climate change. Future advances in supercomputing, alongside reformulation of the models to improve their computational efficiency, will allow us to run simulations at a much higher resolution than ever before. Higher resolution implies improved representation of topographic complexity and of small-scale processes (e.g. convection, gravity waves, ocean eddies) many of which are associated with extreme weather. The new modelling capability will enable study of the atmosphere, ocean and land-surface processes in unprecedented detail, leading to improved understanding, informed design choices for future operational systems and better predictions. New advances and capabilities will also provide the basis for new risk-based hazard predictions in applications such as air-quality, urban planning and future infrastructure resilience.

High resolution modelling must develop in tandem with improvements in our ability to observe the environment both for data assimilation and evaluation of the models. We will maintain our high quality core observing networks and supplement these with data from other sources in order to increase the spatial and temporal resolution of the observations. This will include observations from other systems that contain valuable meteorological information, even if that was not the original aim of the system (e.g. autonomous vehicles), as well as crowd sourced meteorological observations from amateur weather stations with reports of weather impacts.

The increases in data volume arising from moving to higher resolution will rapidly take us beyond the limits of our current approaches and technical tools. Developing a sustainable long-term approach will require a step change in both our technology for data management, processing, and dissemination, and in our decision-making approach in relation to how we design our experiments and their outputs.

Goal

In order to better predict hazards and extremes, develop the next generation of very high resolution global and regional environmental prediction systems, based on global convection-permitting atmosphere models coupled to eddy-resolving ocean models and eddy-permitting regional atmosphere models coupled to estuary-resolving shelf-seas models.

To achieve this vision by 2030 we aim to:

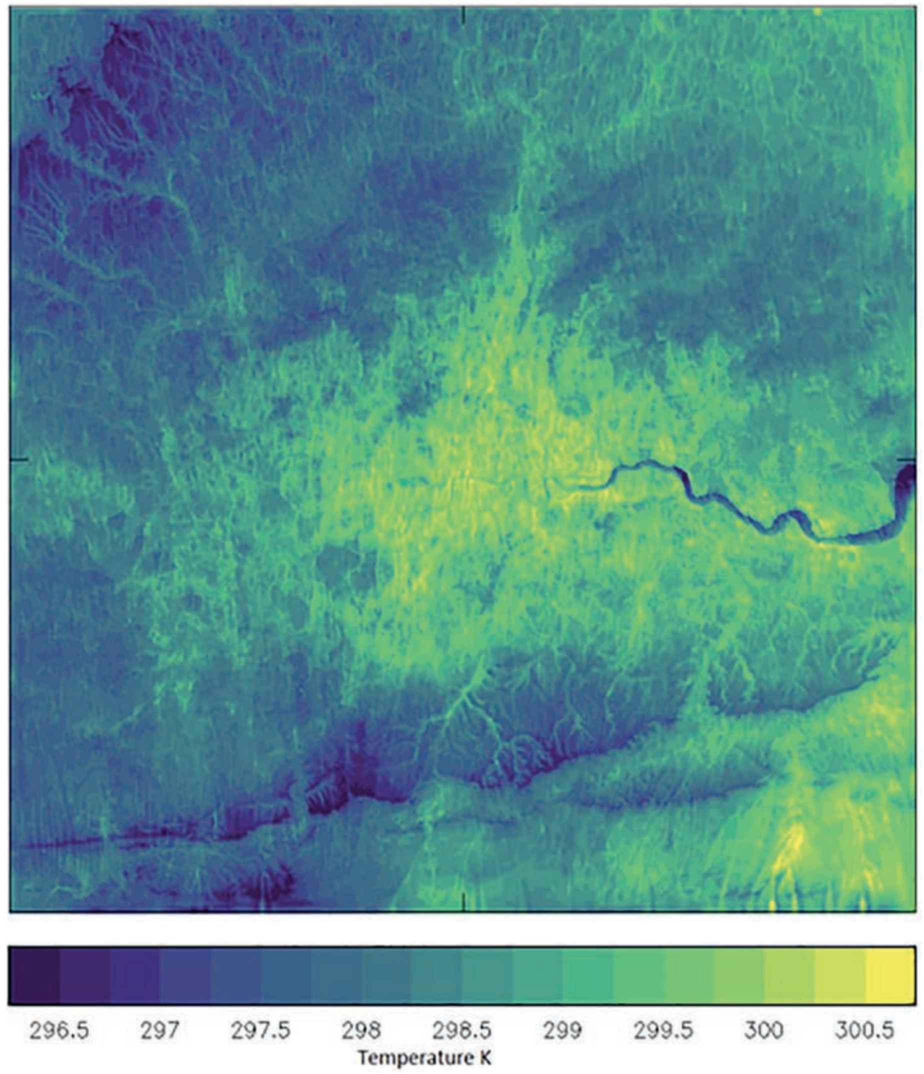
1. Achieve a step change in global and regional simulation, improving simulation quality across timescales in a seamless manner, through resolving the small-scale processes and their interactions with the larger scale which are known to be important for predicting high-impact weather and marine events.
2. For global models, develop a capability for coupled global weather and climate modelling, with horizontal grid lengths smaller than 5 kilometres and corresponding fine vertical resolution. This will be a global convection-permitting atmosphere model coupled to an eddy-resolving ocean model.
3. For regional models, develop a capability for coupled regional modelling, with horizontal grid lengths smaller than 100 metres and corresponding fine vertical resolution. This will be an eddy-permitting atmosphere model coupled to an estuary-resolving shelf-seas model, suitable for urban-scale prediction.
4. For observations, utilise the full capability of our existing networks including the exploitation of three-dimensional radar data and develop a capability to observe atmosphere, land and ocean processes at scales relevant to those features resolved at the new modelling scales for both model initialisation (via data assimilation) and evaluation. This will include use of opportunistic observations, remote sensing, ground-based and airborne research measurements, and the development of new novel field observation strategies and instrumentation. Engagement with partners will be critically important in this area.
5. Improve simulation quality through better representation of small-scale processes (including scale-aware parametrizations) and their nonlinear scale interactions and through improved representation of impacts e.g. at river catchment or on urban scales.

Case study

Urban-scale modelling

With a large proportion of the world population living in cities urban environmental hazards (for example urban heat, air quality and flooding) are becoming more important to forecast on both weather and climate timescales. The current generation of kilometre-scale weather and climate models can only crudely represent effects of cities on weather and small-scale phenomena in the atmosphere such as convection.

However, with grid-lengths of order 100 m the heterogeneity of the urban environment is much better resolved and gradients across neighbourhood scales are captured by the models. The detailed predictions provided by such models could be used for both real-time forecasting of weather hazards and for long term planning purposes, for example to help inform local air quality policy and regulation.



Instantaneous screen level temperature (degrees Kelvin) in a 100 m simulation over London. The detailed signature of small-scale features in the land surface (e.g. valleys and the River Thames) are visible.

Future observations to support high resolution model development and evaluation

As our modelling systems become increasingly able to resolve small-scale processes, observations will play a crucial role in developing the fundamental understanding needed to guide development, providing well constrained cases for evaluation, and meeting the increasing demands of model initialisation. Strategic partnerships will be needed to fully utilise observation infrastructure and to gain maximum benefit from national and international field experiments.

This will require:

- State-of-the-art measurement capabilities that enable small-scale processes to be observed with sufficient detail and accuracy to advance process-level understanding. In a field where scientific advances and technical developments often go hand-in-hand, this will involve the development of customised instrumentation and data processing.
- Development of novel experimental methodologies for observing processes with increased focus on coupling between the atmosphere, land and ocean, and on understanding variability at small spatial scales. This will involve coordinating the deployment of surface and airborne platforms to study processes contributing most significantly to model uncertainty, including convective, stable boundary layer, cloud/aerosol and radiative transfer phenomena. Comprehensive short-term field deployments will be complimented by increasing use of long-term remote sensing observations of clouds, dynamics and thermodynamics.
- Use of research-grade observations to improve understanding of instrument performance and data products from current and future operational surface, airborne and satellite observing systems. These systems offer the wide coverage, continuous datasets needed for model verification, data assimilation and short-range nowcasting.
- Exploration of new observing strategies including the use of distributed opportunistic networks to provide high spatial density information and emerging sensor platforms such as UAVs, connected vehicles and marine AIS systems.

An instrumented Unmanned Aerial Vehicle (UAV) developed at the Met Office boundary-layer research facility in Cardington, UK. The UAV is equipped with instrumentation to make high-resolution vertical profile measurements of temperature, humidity and wind through the depth of the boundary layer.

Producing and exploiting ensembles

Ensemble prediction is a cornerstone of modern weather and climate science. It accounts for forecast uncertainty and identifies the expected range of possible future conditions. The information provided by ensembles also helps to extract predictable signals, provide improved forecasts and assess the risk from extreme events.

In order to maximise the value of ensemble prediction it is important that forecast systems are well designed to maximise skill while optimising spread and maintaining reliability. Automated products need to be ensemble based and operational meteorologists should be able to exploit the vast information content contained within the ensemble members. Uncertainty and the possibilities for extreme events should be communicated effectively to customers and stakeholders in order to improve decision making from weather forecasts, improve near-term planning from predictions of the seasons or years ahead and improve strategic planning from projections of climate for the coming decades.

The Met Office is already a world-leader in the research and operational production of ensembles, but we aim to expand their use across our research, operational predictions and real-time warnings. This will allow our customers to make even better-informed risk-based decisions on all timescales.

Goal

In order to include forecasts of uncertainty at the heart of our endeavour, develop ensemble-based systems and exploit them for prediction across timescales, while developing new and novel uses of ensemble information for improved understanding of weather and climate.

To achieve this vision by 2030 we aim to:

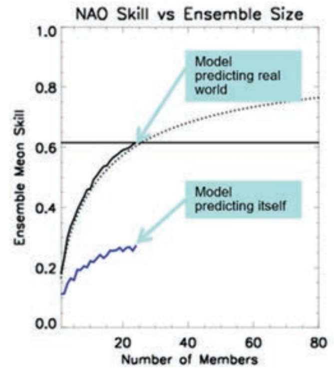
1. Transform operational prediction to be based on probabilities and impact, at time ranges from nowcasts to climate change projections and develop approaches to communicate forecast uncertainty and associated risk.
2. Estimate the limits of predictability for the UK and worldwide regions across different temporal and spatial scales and develop ensemble forecast systems whose skill approaches these limits.
3. Understand the cause of errors in ensemble forecasts and the differences across timescales and phenomena. Use this to help drive next generation model and forecast development.
4. Represent uncertainty in observations across timescales through ensemble data assimilation and represent uncertainty in regional models down to convection-permitting model scales.
5. Investigate new and innovative uses of ensemble information using sub-setting techniques to understand weather and climate variability, develop pathways to different scenarios, provide well calibrated probabilistic forecasts and better anticipate extreme events.
6. Use ensemble systems that provide reliable uncertainty information across timescales for service applications, including risk assessment, decision-making and impacts studies.

Case studies

Effects of ensemble size on prediction skill

Ensemble forecasts contain predictable signals and unpredictable variability due to the sensitivity of atmospheric forecasts to small perturbations. While differences between ensemble members are useful for estimating forecast uncertainty and highlighting possible pathways to extreme weather and climate, they can also obscure the underlying predictable signal. By taking the ensemble average we can average out the unpredictable components of an ensemble forecast to reveal the common underlying predictable signal.

The example shown in the figure is for seasonal predictions of the North Atlantic Oscillation (the single largest factor in the year to year variations in UK winter weather). Correlation scores increase systematically with ensemble size, demonstrating increasingly skilful predictions of the observed evolution of the atmosphere as ensemble size increases (black line). While this demonstrates the importance of ensemble size, a similar analysis using single forecast members as the truth reveals that the forecast ensemble produces more skilful predictions of the real world than itself. This so-called 'signal to noise paradox' has now been found in multiple forecast systems and in predictions on all timescales from monthly to inter-decadal climate change.

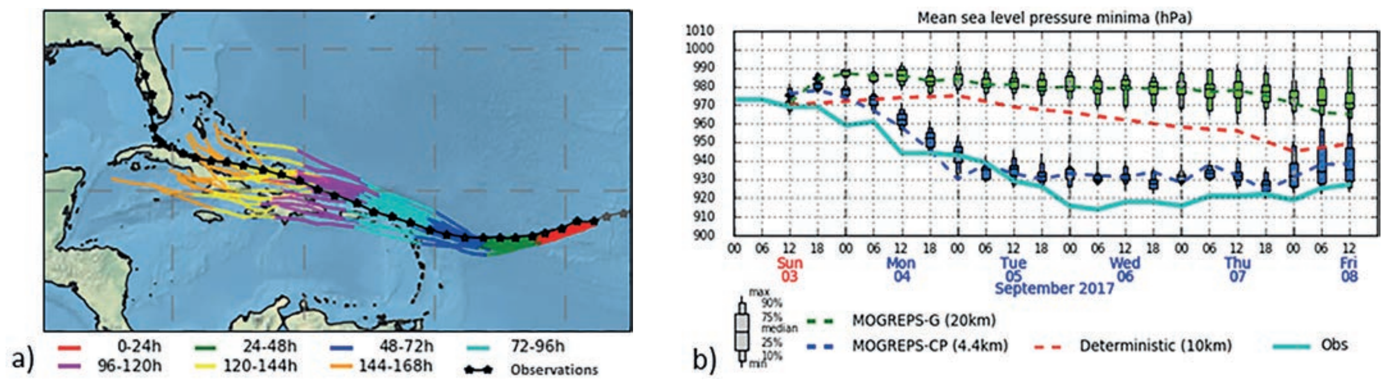


Increasing skill of winter seasonal predictions with ensemble size. The black solid curve shows correlation scores of forecasts for Dec-Jan-Feb mean North Atlantic Oscillation as a function of ensemble size of up to 24 members. The blue line shows the same quantity for the model ensemble mean verified against single ensemble members. The difference between the two illustrates the 'signal to noise paradox' whereby models are better at predicting the real world than themselves.

Ensemble tropical cyclone forecasts

Tropical cyclones (TCs) are one of the most destructive meteorological phenomena around the world. Global ensemble forecasts are currently used to provide estimates of uncertainty on the tracks and intensity of TCs.

Currently, convection-permitting ensembles are used in demonstration mode and they have the potential to better represent TC intensity. In the future, increased computing capacity will allow convection-permitting ensembles to be run operationally for TCs, enhancing forecasts and warnings for these devastating storms in support of our international partners and civil protection agencies.



Forecasts for Hurricane Irma (September 2017) from the MOGREPS-G global ensemble (20 km resolution) and the equivalent prototype MOGREPS-CP convection permitting 4.4 km ensemble: a) 7-day track forecast from MOGREPS-G; b) 5-day intensity forecasts (minimum sea-level pressure) from both MOGREPS-G and MOGREPS-CP, illustrating how the 4.4 km model provides a much better forecast for the rapid intensification on 4 September.

Capturing environmental complexity

Alongside increases in resolution and advances in ensemble prediction, including relevant environmental complexity in our seamless simulations will be crucial in order to meet demands for improvements in forecasting ability and climate prediction across all time and spatial scales. The Earth's climate and weather systems are heavily influenced by factors and processes such as the carbon cycle, vegetation, wildfires and sea-ice cover. By observing and integrating these feedbacks into our models, we will gain a deeper fundamental understanding of the Earth System vital for both short-term and long-term environmental prediction. As our climate warms, ice cover declines and land use changes due to human intervention. Understanding the impact of this will be essential to improve projections of sea-level rise and carbon release to inform climate mitigation policy. For the UK and global partners to meet key Paris emissions targets and prepare for the consequences of climate change, advice must contain accurately quantified global carbon budgets, climate pathways, and a developed knowledge of dangerous tipping points and their impacts. An increased understanding of the Earth System is vital for dispensing this advice. The move towards environmental prediction will be key to understanding how we can optimise human interaction with the natural environment and promote clean growth on local, national and international scales.

Goal

To extend our environmental prediction capability with a focus air quality, the water cycle and carbon and nitrogen cycles in order to improve our forecasts, climate projections, hazard prediction and advice on global climate change mitigation.

The areas we will particularly focus on are:

- The carbon cycle, carbon budgets and nitrogen cycle
- Atmospheric composition, aerosols and air quality
- Hydrology and water budgets and impacts
- Physical process complexity e.g. in-cloud microphysics

To achieve this vision by 2030 we aim to:

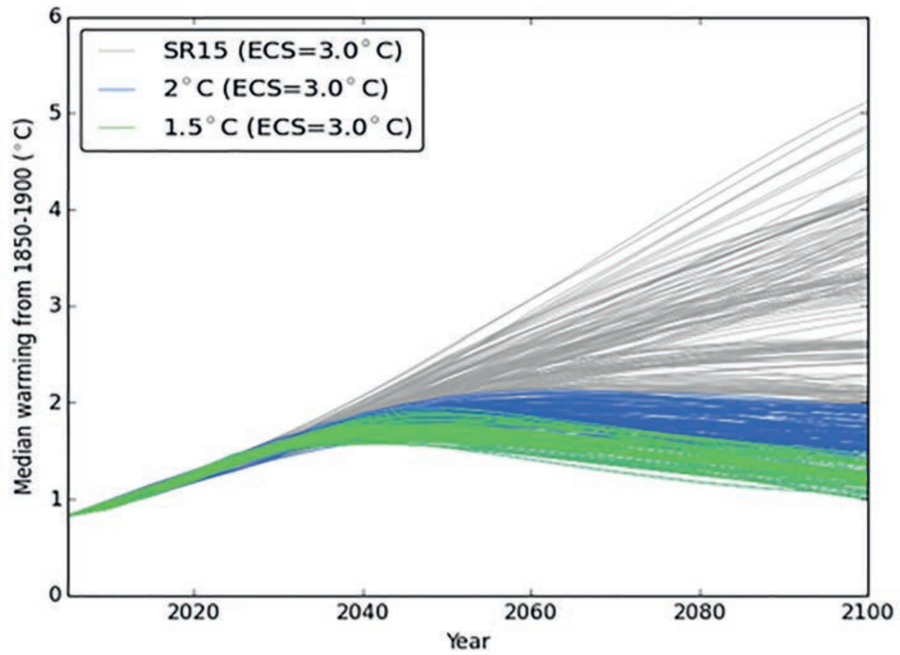
1. Develop, improve and include the newest and most relevant Earth system feedbacks in global models across timescales, with a particular focus on carbon, air quality and water.
2. Develop, improve and include representations of relevant complexity for a regional environmental forecasting and projection capability, using relocatable coupled prediction systems, with a focus on hydrology, marine processes, air quality and biogeochemistry.
3. Deliver new and improved capability to combine observations and models in a variety of ways, including tools for: evaluation of processes and model performance; ability to constrain forecasts with observations through coupled assimilation approaches (including quantities such as atmospheric composition); identification and application of emergent constraints; and to monitor and detect long-term changes through attribution approaches and inversion modelling.
4. Probe the workings of the Earth system using our world-class modelling systems as a computational laboratory.

Case studies

Climate mitigation targets

Through the 2015 Paris agreement the UK government has committed to reduce carbon emissions to limit global warming to 1.5°C, and recently also committed to net zero emissions by 2050. To ensure the UK and its international partners meet these targets it will be crucial to understand options for meeting carbon budgets (such as biofuel, tree-planting, carbon capture), the climate and emissions pathways compatible with a range of climate targets and the key climate tipping points associated different levels of future warming.

Increased complexity in Earth System Models will allow us to explore these interactions in more detail. The addition of climate-system processes such as wildfire, permafrost and nitrogen and tailored experiments to explore the impact of land-use change scenarios (e.g. increased use of biofuels) or ice sheet melting will allow us to better determine the impacts under different emissions scenarios, allowable carbon budgets to constrain warming to 1.5 degrees, and explore the effectiveness of carbon mitigation/offsetting options.



Median warming estimated for the scenarios used in the IPCC 1.5°C special report, reprocessed with an equilibrium climate sensitivity of 3°C. The grey pathways exceed 2°C in 2100. Lack of global cooperation, lack of governance of the required energy and land transformation and increases in resource-intensive consumption are key impediments to achieving the 1.5°C target.

The blue pathways limit 2100 warming to below 2°C. This would require mitigation pathways characterized by energy-demand reductions, decarbonisation of electricity and other fuels, electrification of energy end use, deep reductions in agricultural emissions, and some form of Carbon Dioxide Removal (CDR) with carbon storage on land or sequestration in geological reservoirs

The green pathways limit 2100 warming to below 1.5°C. In comparison to a 2°C limit, the transformations required to limit warming to 1.5°C are qualitatively similar but more pronounced and rapid over the next decades. Limiting warming to 1.5°C implies reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers, particularly methane. Even if this is achieved, temperatures would only be expected to remain below the 1.5°C threshold if the actual geophysical response ends up being towards the low end of the currently estimated uncertainty range.

Seamless environmental prediction

Central to the mission of the Met Office is accurate and timely prediction of weather, seasonal and near-term climate hazards, and understanding how these hazards will evolve under a changing climate. Our world-leading seamless prediction capability is the primary tool for this. We will continue to improve its accuracy and develop capability to support the new services required by society.

Goal

Further develop our world-leading seamless environmental prediction capability, whereby a single model family is used in conjunction with observations and theory to quantify weather hazards in the past, in present day climate and into the future across weather and climate timescales.

To achieve this vision by 2030 we aim to:

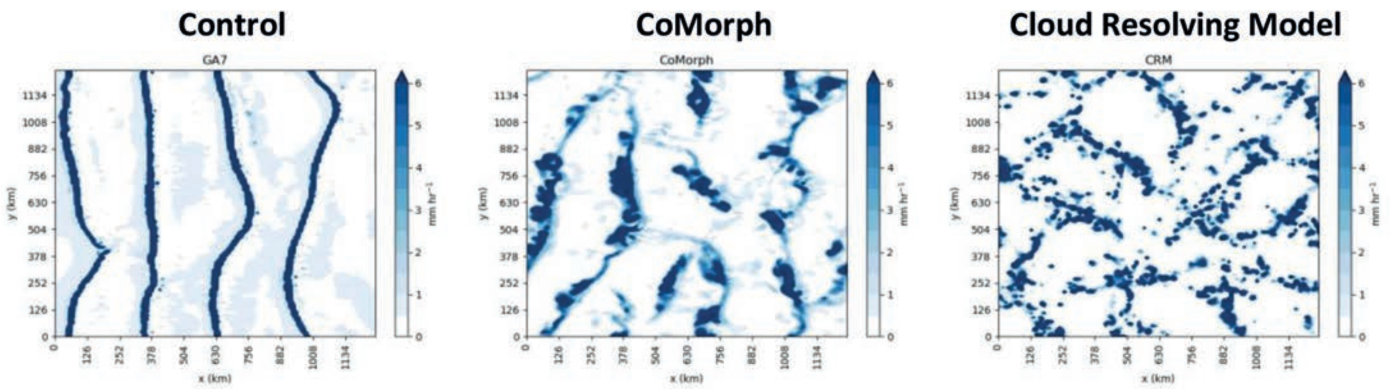
1. Develop improved global and regional seamless coupled ensemble prediction systems, based on the atmosphere, marine, land and cryosphere component models and building on the pioneering research from the Path to High Resolution and Producing and Exploiting Ensembles themes.
2. Building on the Capturing Environmental Complexity theme, develop a traceable approach to incorporating complex processes into the seamless prediction systems. This allows evaluation across all timescales and choices around complexity in operational models.
3. Improve the representation of the current (initial) state of the Earth system through development of new observation monitoring and ensemble based data assimilation techniques that take advantage of existing and new observations, improving analysis quality and the skill of our seamless predictions.
4. Confront weather and climate predictions with observations to continuously assess model skill and predictability across a variety of time and space scales and inform future developments, and to harness the promise of the technique of emergent observational constraints in grounding model predictions.
5. Use the seamless environmental prediction capability to study, assess and monitor past, present-day and future weather and climate hazards through global and UK observational datasets and innovative use of model/ensemble datasets. This will inform delivery of Science to Services through the Research to Production and Hazard to Decision Making themes.

Case study

Convection

The precipitation, lightning and severe turbulence associated with deep convection make it a significant weather hazard. Deep convection responds locally to instability, but it also transfers heat upscale such that conditions on the planetary scale depend on, organise, and interact with it. It is the simultaneous need to represent the small length-scales of the buoyant transport and its influence on global scales that make it a long-standing problem for atmospheric modelling. A realistic representation of convection is critically important for our seamless predictive capability of past, present and future weather hazards.

Currently, we have a disconnect in our seamless modelling systems in that we use parametrized convection in simulations with grid resolutions coarser than 10 km and no parametrized convection at 4 km and higher resolutions. This convective “grey zone” where convection is partially resolved applies across grid spacings ranging from approximately 100 m up to 10-20 km. In collaboration with our UK academic partners (funded via the Natural Environment Research Council ParaCon project) we are developing a new convection parametrization scheme (CoMorph) that aims to produce more realistic behaviour than earlier schemes at all resolutions. The new scheme will also have the ability to adapt to the size of the model grid, so that it performs well across the range of resolutions, and so remove a break in our seamless modelling systems. This will be a crucial step in developing kilometre-scale global modelling capability.

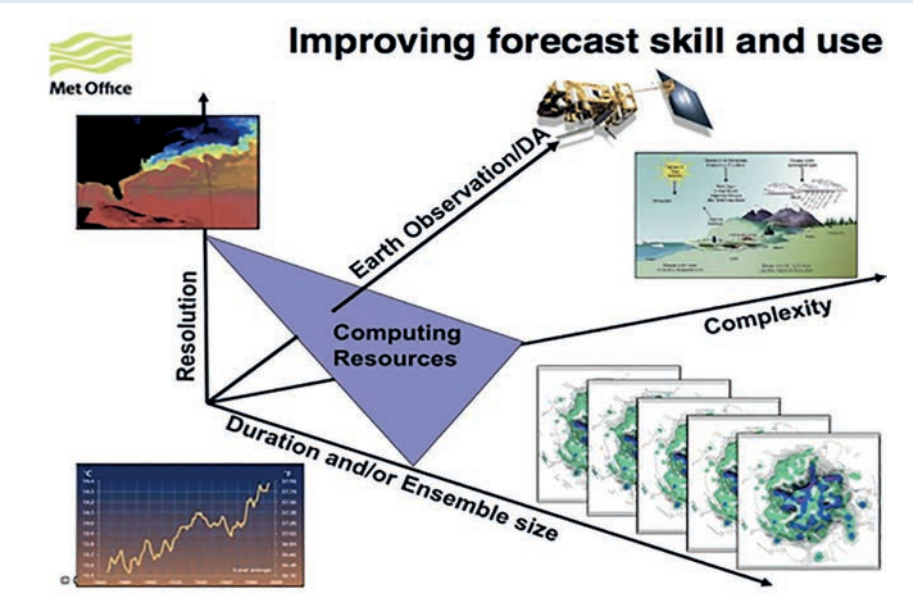


Surface rain rates in idealised model experiments. These allow us to investigate the behaviour of convection parametrization schemes in a controlled environment. Left: The control convection scheme currently operational in the UM, Centre: a prototype of the new CoMorph scheme, Right: a cloud resolving reference simulation at 1 km resolution. The structures within the new scheme better resemble their higher-resolution counterparts.

The trade-off between complexity, ensembles and resolution

Although advances in technology and next generation modelling will enable us to take advantage of increases in computing power, we will always be constrained by available supercomputing capacity. As noted in this strategy, we aim to introduce higher resolution, greater use of ensembles and increased complexity into our modelling system in order to improve our scientific capabilities and the services we provide. However, with limits in supercomputer capacity there is a trade-off between these three axes and different research questions will require different model configurations to optimise outputs and benefits. The precise balance will be informed by the user needs for our services. We aim to develop a traceable modelling hierarchy with preferential configurations for each application, based on evidence-based tensioning of resolution, complexity and ensembles. This traceable hierarchy will provide the tools needed to achieve different balances of complexity, resolution and ensemble size in different applications. To achieve this we will:

- Pioneer in the model development space and push the boundaries of traceable models in the direction of ensemble size, resolution and complexity;
- Determine the appropriate level of ensemble size, resolution and complexity for each application and a process to understand the cost and benefits for each application;
- Consider the benefit of hybrid system designs (e.g. mixed resolutions or complexity), which could take advantage of machine learning in their formulation or the formulation of their components.



A schematic illustration of the competing factors for computing and human resources to deliver improved predictions and projections across timescales.

Next generation modelling systems

For around 50 years the power of supercomputers has played an ever-increasing impact in the delivery of scientific breakthroughs, many of which have had a direct and dramatic impact on people's lives. Computer simulation has been critical to advances in weather and climate predictions driving what has been referred to as the "quiet revolution" in forecasting capability. It has also driven improvements in our ability to predict weather and climate events more accurately, with greater regional detail and on longer timescales. Advances in weather and climate science are now inextricably linked with increased supercomputing power and exploiting that increased power will be needed to implement the pioneering improvements outlined in this strategy. But fundamental engineering limitations mean that the landscape of supercomputer architectures is changing dramatically, as physical constraints on micro-electronics mean that future increases in the speed of computation will place significant demands on the flexibility, adaptability and scalability of our codes. Therefore, in order to deliver this strategy, continue to improve our services and maintain our world-leading position in weather and climate simulation, a radical redesign of our codes is required for the supercomputers of the future. This transformation of our model structures will also provide many new exciting opportunities, unlocking new modelling potential so that our scientific ambition is freed from the limits of current technology.

Goal

Revolutionise the Met Office's complete weather and climate research and operational simulation systems so that the Met Office and its partners are ready to fully exploit future generations of supercomputer.

To achieve this vision by 2030 we aim to:

1. Weather and climate research and prediction systems that are designed for future generations of supercomputers, unlocking new scientific potential.
2. An end-to-end modelling system, from observations through simulation to model output, which is future-proofed to changing supercomputing design, employing a "separation of concerns" concept to divorce scientific algorithms from architecture-dependent code optimisation.
3. Newly designed models and systems that are easy to use, portable and easily accessed by our partners and stakeholders, focusing on community development wherever appropriate.
4. A network of new pioneering collaborations and strengthened partnerships working with the Met Office at the forefront of next generation modelling systems, with a particular focus on fostering a community of practice of computational scientists and software engineers across the UK.

Case study

Usability of our code

The Unified Model is a complex system that can be used for anything from research into cloud processes to thousand year long Earth System simulations, from simulating flow within a laboratory's rotating water tank to simulating the temperature field on a tidally-locked exoplanet. It has around a million lines of code and has grown organically over the last 30 years. It is perhaps therefore not surprising that it can be quite challenging for a new user to access the code, set up the experiment that they want and then get their changes committed back into the modelling system. This can limit the appeal of working with the UM, particularly for academic users whose interest might be part of a rapidly evolving PhD project.

The Next Generation Modelling Systems theme presents a golden opportunity to build a system that is much more readily accessible to a wider community. Our vision is that the new system will be managed in a way that enables ready access to the codes and allows collaborators to easily benefit personally from any contributions that they make. The system itself will be designed around modern software practices that are designed with the user in mind. This should make accessing and running the model a more straightforward process. To achieve this, it is essential that we recognise where our expertise lies; where appropriate, instead of developing codes ourselves, we will aim to capitalise on the expertise of others, building long term partnerships with them to deliver a mutually beneficial capability.

The LFRic Diagnostics project team in 2020. This team is contributing to the delivery of a modelling system that is fit for future computers by developing a radically new software infrastructure to replace that of the Unified Model. The name LFRic was chosen in recognition of Lewis Fry Richardson and his vision for how to make a weather forecast. Richardson's fantasy for how to achieve this was to solve the equations of motion by coordinating the efforts of thousands of human processors, each one working on their own small area of Earth's atmosphere - an approach remarkably similar to how we use the thousands of processors within a modern supercomputer.

Fusing simulation with data science

Data Science is a rapidly developing area, with countless applications across science and technology. It is already delivering breakthroughs in a broad range of disciplines such as image recognition, machine translation, radiology and protein-folding prediction. As data science techniques are developed further, the exploitation of these approaches will be vital in order to remain competitive and maintain our position as world-leading in weather and climate science. While we already apply data science and machine learning techniques in our modelling systems, particularly in data assimilation, we will expand their use and explore how they can help us meet future challenges and deliver cutting-edge science. Machine learning may help us adapt to the higher resolution and greater volumes of data brought by the next generation of supercomputers and improve efficiency across the whole modelling system – from observations through to products. Combined with our domain expertise in weather and climate data and applications, modern data science techniques will provide opportunities for innovation in weather and climate science and services.

Goal

Use new and evolving data science methods such as artificial intelligence and machine learning and advanced data assimilation in order to remain at the cutting edge of weather and climate prediction and services.

To achieve this vision by 2030 we aim to:

1. Make available appropriate training, tools and expert advice so that we can take advantage of new data science techniques for research.
2. Run a range of feasibility projects across Met Office science areas and identify key areas for resourcing and capability development.
3. Implement an appropriate level of use of machine learning and data science across all Met Office research and innovation activities, where this gives a clear benefit in terms of improved predictive skill, capability, efficiency or reduced costs.

There are many examples of opportunities to use machine learning and data analytics:

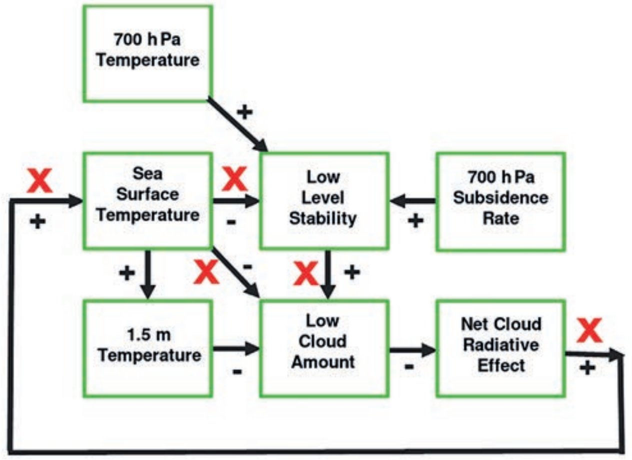
- Weather observations – observation pre-processing, data thinning, proxy data and observation repair
- Climate observations – quality control, error characterisation and data rescue
- Data assimilation – data and dynamical systems, generation of perturbation-forecast models and observation operator optimisation
- Simulation tools – parametrization emulation, numerical methods, model evaluation and error attribution
- Simulations – climate model output emulation, high resolution downscaling and observation-driven nowcasting
- Operational hazard products – sub-setting ensembles, post processing and data driven ensemble generation
- Hazard to impacts – for applications such as severe weather warnings and defence
- Underpinning scientific research – the use of data analytics and 'unsupervised' learning to yield new insights

Case studies

Analysis of cloud variables from climate model data using a Self-Organising Map

Supervised machine learning techniques (such as Deep Neural Networks) have made impressive progress in solving hard problems in image and speech recognition and are now gaining popularity in weather and climate science. Unsupervised learning has received less attention but may be used to extract new insights from observations and models. An example is the Self-Organising Map (SOM) which is an effective dimension-reduction and clustering technique capable of identifying non-linear relationships in data. SOMs are in principle capable of detecting relationships which will not be apparent using conventional linear correlation analysis.

We can use SOMs to investigate relationships between clouds and cloud-controlling factors in observations and climate model simulations of the low-level stratocumulus deck off the coast of California. SOMs are able to detect strong relationships between variables that are missed or only weakly detected by linear correlation analysis.

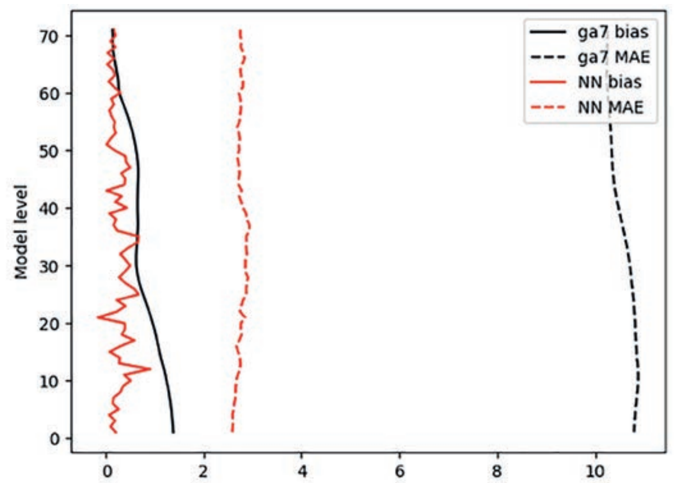


Relationships between subtropical low cloud and cloud controlling factors in observations are shown by arrows, and the signs indicate the sign of covariation. The current version of the climate model captures many of these relationships but some are weaker than observed (red x symbols). Insights from this work can be used to improve relationships between clouds.

Machine Learning in physical parametrizations

Parametrizations of unresolved processes such as convection, radiation, or microphysics, account for a large proportion of the computational cost of model simulations. Parametrization schemes are crucial in maintaining the forecast accuracy at all lead times but errors in the schemes arise from uncertainties in the underlying physics and from simplifications introduced to speed up the calculations. Recent developments in the field of Machine Learning (ML) have the potential to help on both these fronts.

For example, ML approaches are able to emulate the radiative transfer scheme SOCRATES, demonstrating their potential for representing complex relationships between resolved and unresolved processes. In the case of radiative transfer, the underlying physics are well understood but solving the full equations in an operational setting is impractical. However, SOCRATES can be run offline at very high spectral resolution to generate high quality training data for a deep neural net (NN) emulator. The NN architecture can be optimised to reduce the mean absolute error, improving the accuracy relative to the operational scheme. More generally, depending on the application, the complexity of the NN can be tuned either to minimise computational cost or maximise accuracy.



Vertical profiles of errors in shortwave radiation from a machine learning approach (a deep neural net emulator, NN) and a traditional parametrization scheme (the current GA7 scheme). The errors shown are the bias (solid) and mean absolute error (MAE, dashed) and are relative to a high spectral resolution benchmark. The machine learning approach provides a more accurate prediction.

Cross-cutting themes

People

The nature of work, workplace and the workforce is changing. Ensuring the Met Office has the capabilities it needs to deliver our purpose and can gain competitive advantage through our people will depend on being prepared for these changes.

Those now entering the workforce have different expectations of work where high-quality work, flexible working and variety are important. Requirements to innovate alongside existing delivery bring challenges to balance traditional hierarchical structures and processes with greater innovation and agility. There is also a growing shortage and competition for STEM skills which are fundamental to our success. Meanwhile, our sources of Government funding are coming under increasing pressure which will likely result in challenging prioritisation decisions. Our approach needs to ensure we maximise the value and return on investment of our people through building effective ways of working, systems and processes.

With this in mind, our “People vision” is to lead and invest in our people and culture to make the Met Office a great place to a work. The People Strategy is a long-term plan that ensures we deliver on our people vision and keep our commitment to making the Met Office a great place to work.

Goal

Over the next 10 years we will focus on the following areas, aiming to:

1. Transform our leadership capability. We will continue to invest in developing our managers and leaders to ensure we have the right behaviours, skills and knowledge to drive success.
2. Enhance equality, diversity and inclusion. We will also work to make our organisation more reflective of the world we live in and the communities that we serve.
3. Enable and develop people. We will strive to give you the space and the resources you need to develop the people and technical skills that benefit you and our customers.
4. Underpin this work by transforming the way we manage people information.

Case study

Joint roles for Operational Meteorologists

Within the Future of Operational Meteorology Programme, the Met Office aims to develop a multi-faceted, diversified workforce supported by a professional skills framework, a career pathway and internal placement opportunities. This will lead to varied and interesting careers, whilst the Met Office can make the best use of the talent within the Op Met community.

Working across Operational Meteorology, Climate Science and Communications, the Met Office has developed two brand new pilot roles for the next financial year (2020-21). The job holders will combine their knowledge of the weather and how it impacts people, with their understanding of how climate change is impacting the weather. They will then communicate the impact of climate change on current weather events to customers and stakeholders.

Mairead Cooke will begin one of the brand new pilot roles in 2021.

Partnerships

The ambition and vision contained within this strategy can only be realised by working in partnership. We will continue to strengthen and expand our network of partnerships with exceptional organisations both nationally and internationally. We will develop and nurture these partnerships and seek to complement our own expertise with that of others to support delivery of this Strategy. Our ongoing commitment to partnership working enables us to co-develop the exceptional science and innovation needed to serve the full breadth of our societal need for services, while developing and maintaining the critical operational infrastructure.

Goal

Over the next 10 years we will focus on the following areas, aiming to:

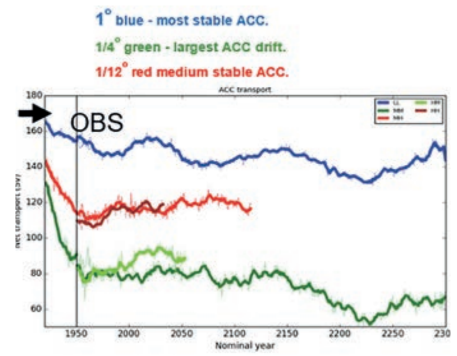
1. Develop and nurture our existing partnerships with exceptional organisations around the world. Delivery of the Strategy depends upon our ability to work efficiently and effectively with world-leading organisations and form sustainable relationships built on a shared goal and mutual benefit.
2. Build new partnerships to specifically support delivery of the Research and Innovation themes, particularly Hazard to Decision Making, Fusing Simulation with Data Science and Next Generation Modelling Systems.
3. Develop formal partnerships with other meteorological services to share best practice around operational delivery. We face common challenges and there is a significant opportunity for us to learn from one another and pool resources and expertise to advance towards our shared goals.
4. Strengthen, evolve and expand the nature of our relationship with partners. We will create new opportunities for secondments, staff exchange and split-working to support enhanced collaboration and technical skills development. We will embark on new and exciting projects with our partners to stretch the boundary of our science or apply it in new and innovative ways.

Case studies

Antarctic Circumpolar Current (ACC)

The Antarctic Circumpolar Current (ACC) is one of the largest ocean currents, it flows clockwise from west to east around Antarctica and it is crucial for maintaining the ice-sheets around this continent. However, the Met Office high resolution CMIP6 model – HadGEM3-GC3.1 HI – has a weak representation of this current, due to substantial near-Antarctic salinity biases which make the active ice-shelf model unsuitable for studying the ACC. The model biases have a substantial dependence on ocean model resolution and are best in the 1° ocean resolution model (see figure). A Process Evaluation Group (PEG) has been created to solve this critical model problem, involving UK universities, NERC centres and Unified Model Partners. It has two strands:

1. Developing a new cloud parametrization linking ice-nucleation and aerosol concentrations in order to alleviate Southern Ocean cloud biases.
2. Understanding the causes of the ocean resolution-dependencies and sensitivities to parametrizations, providing new insight which will help us to improve these model biases.



The eastward volume transport (Sv) through Drake Passage, the strait between South America and the Antarctic Peninsula, for a set of models with different ocean and atmospheric resolutions. The blue, red and green lines represent models at ocean model resolutions of 1° (~100 km), 1/4° (~25 km) and 1/12° (~8 km), respectively. The observational estimate is shown with an arrow.

Innovative Partnerships in the Informatics Lab

The Met Office Informatics Lab is a major partner in the Pangeo community, promoting open, reproducible and scalable science. The Informatics Lab was a founding member of this community, contributing a significant amount of the original technical effort. This has led to two further, related partnerships - with Microsoft Azure and the Alan Turing Institute.

Our partnering with Microsoft is to produce an enterprise-ready version of Pangeo that can be used as a go-to cloud data science platform for the UK via the Alan Turing Institute, as well as being deployed in the Met Office as a data analysis and visualisation platform for use by Met Office scientists and meteorologists.

We are also partnering with Google DeepMind, applying machine learning techniques to weather data. Specifically, this involves the use of machine learning to predict subsequent rainfall radar fields given a series of input fields up to that point.

A synthetic radar image from the nowcasting project with Google DeepMind.

Practices

To remain at the cutting edge, we need a programme of research and innovation that is continually changing and improving; testing new technology and methods and promoting a work-place culture that brings out the best in our people. Our staff must be involved in organisational change to maximise the impact of their work. However, changes take time and resource to implement so we will ensure our staff are able to adapt to the future.

Goal

Over the next 10 years we will focus on the following areas, aiming to:

1. Embrace new approaches as technology and scientific research methods advance. We will continue to innovate and to maximise the impact of our science, for example through advances in exascale computing, cloud computing and data science. As new technology is brought in, we will ensure our staff will be able to adapt to maximise benefits by providing new training.
2. Ensure that our scientists are equipped with and trained for the best industry standard computing, coding, observation and research tools in order to maintain our place as leaders in the international weather and climate science research community.
3. Promote flexible working and progressive workplace policies to support our people's needs, allowing them to thrive.
4. Promote cross-office working by taking a cross-disciplinary approach to projects and problem solving, setting up virtual teams made up of expertise from across the Met Office and establish new multidisciplinary science-operations-technology roles that become a key element of how we work.
5. Maximise the impact of our work by ensuring we continue to focus on prioritising the societal benefits of our work and communicating effectively with stakeholders in order to emphasise the value of our science. Explore new and innovative ways of communicating our science, for example using data visualisations, social media and presentations to academic, industry and government conferences and events.
6. As we continue to evolve to remain at the forefront of what we do, ensure business changes are managed effectively and staff are supported and fully engaged with the required changes.

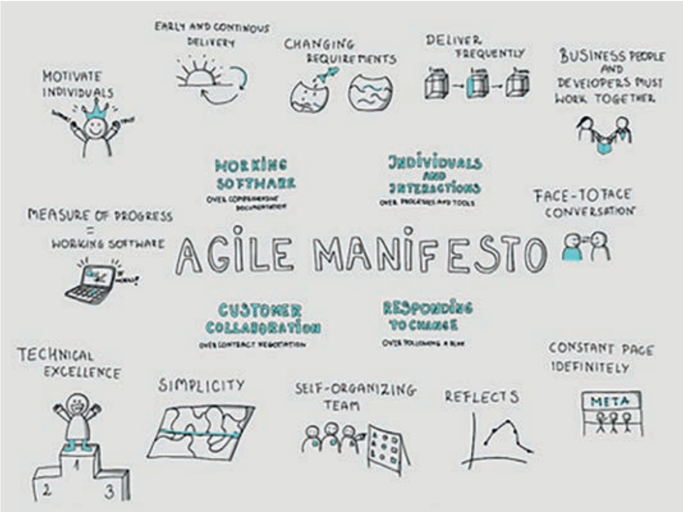
Case study

Agile at the Met Office

VIPP (Verification, Impact and Post-Processing)

"Agile" is an iterative approach to project management and software development that helps teams deliver value to their customers faster. Instead of betting everything on a "big bang" launch, an agile team delivers work in small, but consumable, increments. Requirements, plans, and results are evaluated continuously so teams have a natural mechanism for responding to change quickly. The Agile Manifesto prioritises "individuals and interactions over processes and tools, working software over comprehensive documentation, customer collaboration over contract negotiation and responding to change over following a plan".

The VIPP team is responsible for the science and systems which use output from numerical weather prediction (NWP) models. For four years, parts of VIPP have been using various flavours of Agile, initially starting with 'Scrum' before evolving to a looser continuous workflow, with different styles suiting different people and types of work.



Certain Agile concepts have proved to be extremely valuable, including:

- Daily stand-ups (15-minute discussion of work and issues);
- Sprint demos (monthly presentation of work done to each other and stakeholders);
- Continuous integration (testing);
- Retrospectives (feedback on team efficiency);
- The role of a developer coordinator (Scrum Master) and chief business-prioritiser (Product Owner);

The VIPP team has also found success in other kinds of practices, including the use of Git, GitHub, cloud-based continuous integration (Travis, GitHub Actions), open source, and Python. There are several joint roles with operational meteorologists and a workplace culture geared towards remote and flexible working.

Technology

Technologists frequently face "wicked problems", where requirements only reveal themselves through exposure to potential solutions. They often tackle these problems with Agile methods, where cross-disciplinary teams incrementally build and deploy small parts of the solution and obtain feedback for learning. Value is delivered earlier, more often and in smaller batches, increasing the number of opportunities to make better choices and improve project outcomes. This is an excellent way to both "build the right thing" and "build the thing right" – software development becomes a series of experiments to explore both technologies and user needs.