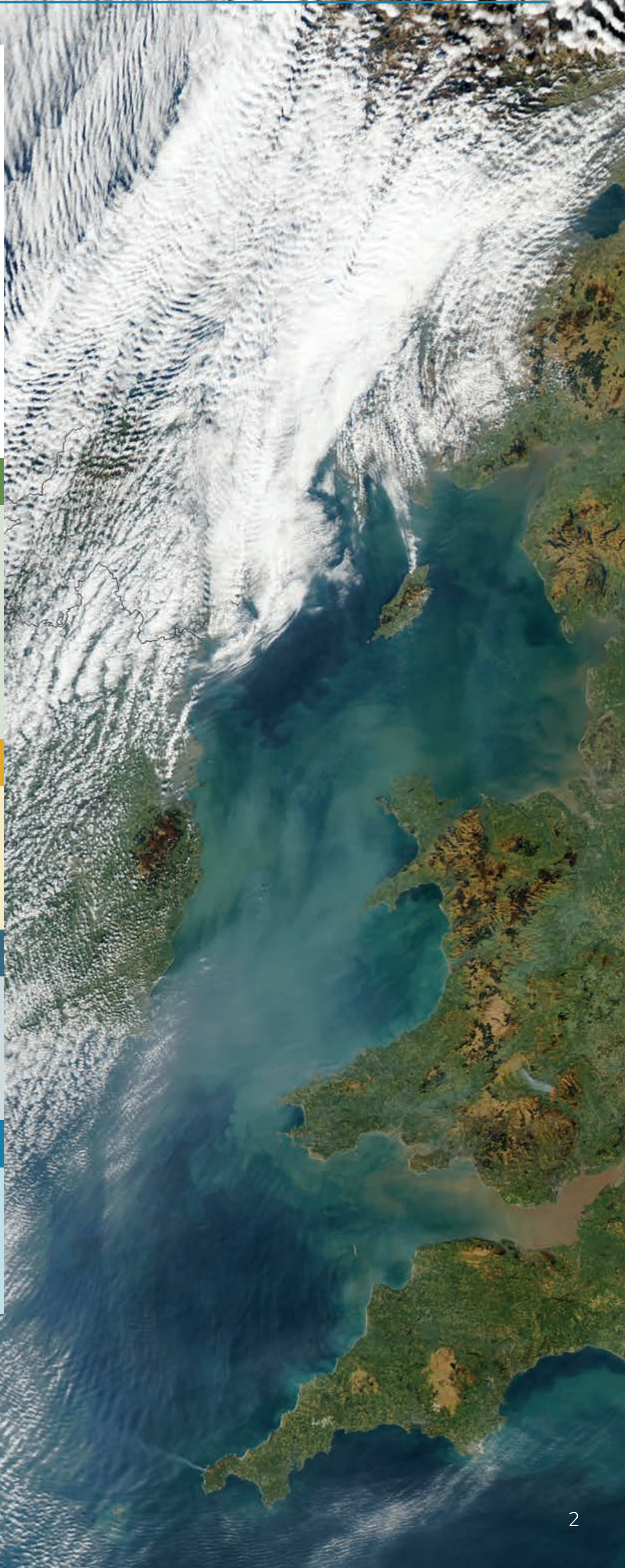
Met Office

Weather and climate science and services in a changing world

Research and Innovation Strategy | May 2022 | v.2

Contents



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 help to minimise the damage and realise the opportunities.

At the same time enabling 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 refreshed version of the Met Office Research and Innovation Strategy introduces our National Capability which combines the driving forces of science, technology, and observations to deliver world-leading weather and climate science and services, support national and international needs, and respond to emergencies. This Strategy also describes the key activities required to advance our National Capability.

It brings together three strands: the new opportunities enabled by pioneering weather and climate science; the future technologies that will radically increase our ability to support weather and climate experts and operational meteorologists to produce forecasts, analyse the data and serve information to our sponsors; and the processing and visualisation of this information to produce guidance. In this way it 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 and technology infrastructure we use to simulate weather and climate to make them fit for purpose for the next generations of high performance and cloud computing. We are eager to use the merging of data sciences, of artificial intelligence and machine learning to complement these simulation tools, to produce the best possible forecast information. Again, we know that we won't be able to do this by ourselves. As we embrace innovative technologies, we will build the right partnerships to fully exploit what we and others can do to meet the needs of our customers. 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.

The Research and Innovation 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

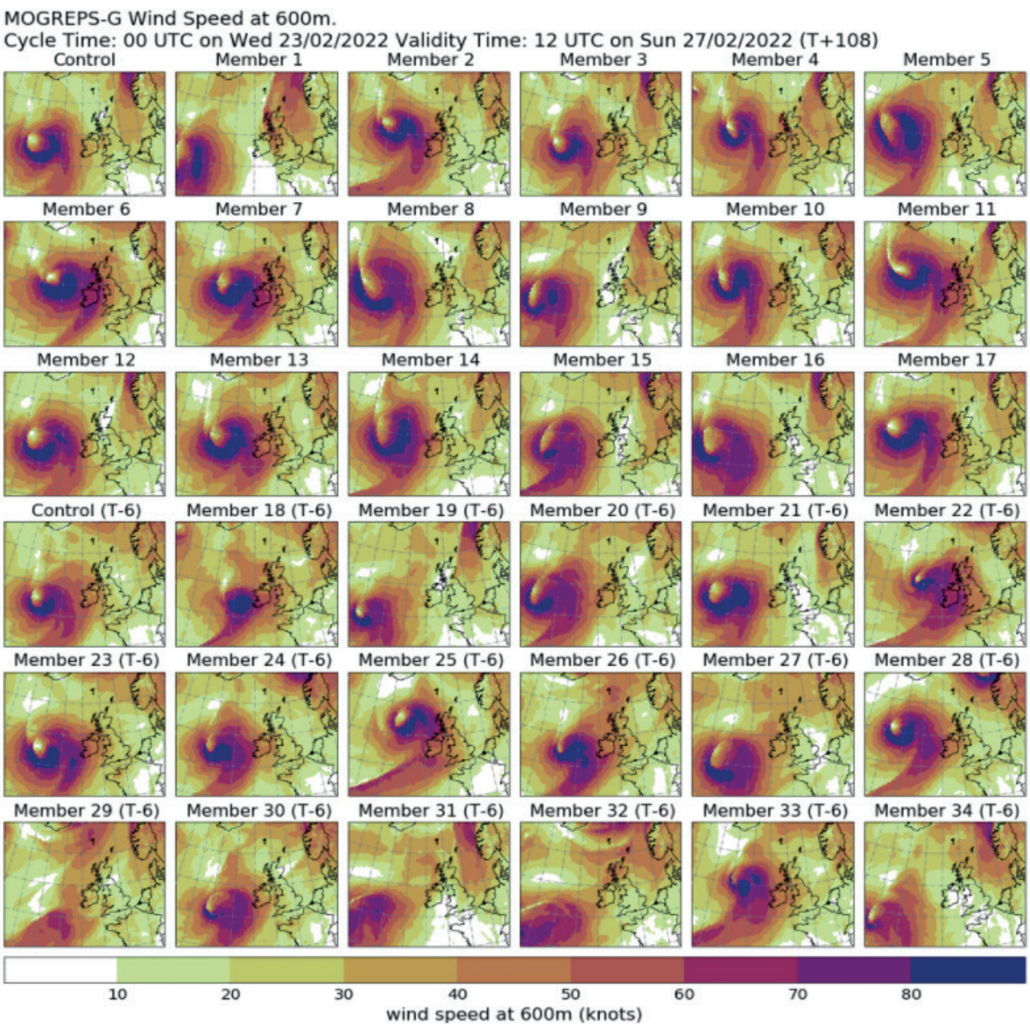
Introduction

Predicting our weather and climate, and their impacts has become one of the most important areas of scientific and technological endeavour. We have seen significant advances in forecasting skill. But there is a constant need for improvement as society drives for greater accuracy, efficiency, and utility. 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 underpinned by around three strategic anchors: Excellent people and culture; Exceptional science, technology and operations; and Extraordinary impact and benefit. These strategic anchors will be delivered through our People, Research and Innovation and Impact and Benefit strategies.

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. 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 nowcasting, to weather forecasts through to climate change projections. We provide 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 ambitious Research and Innovation Strategy builds on this 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 purpose - Why we exist

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

Our vision - What we want to achieve

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

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

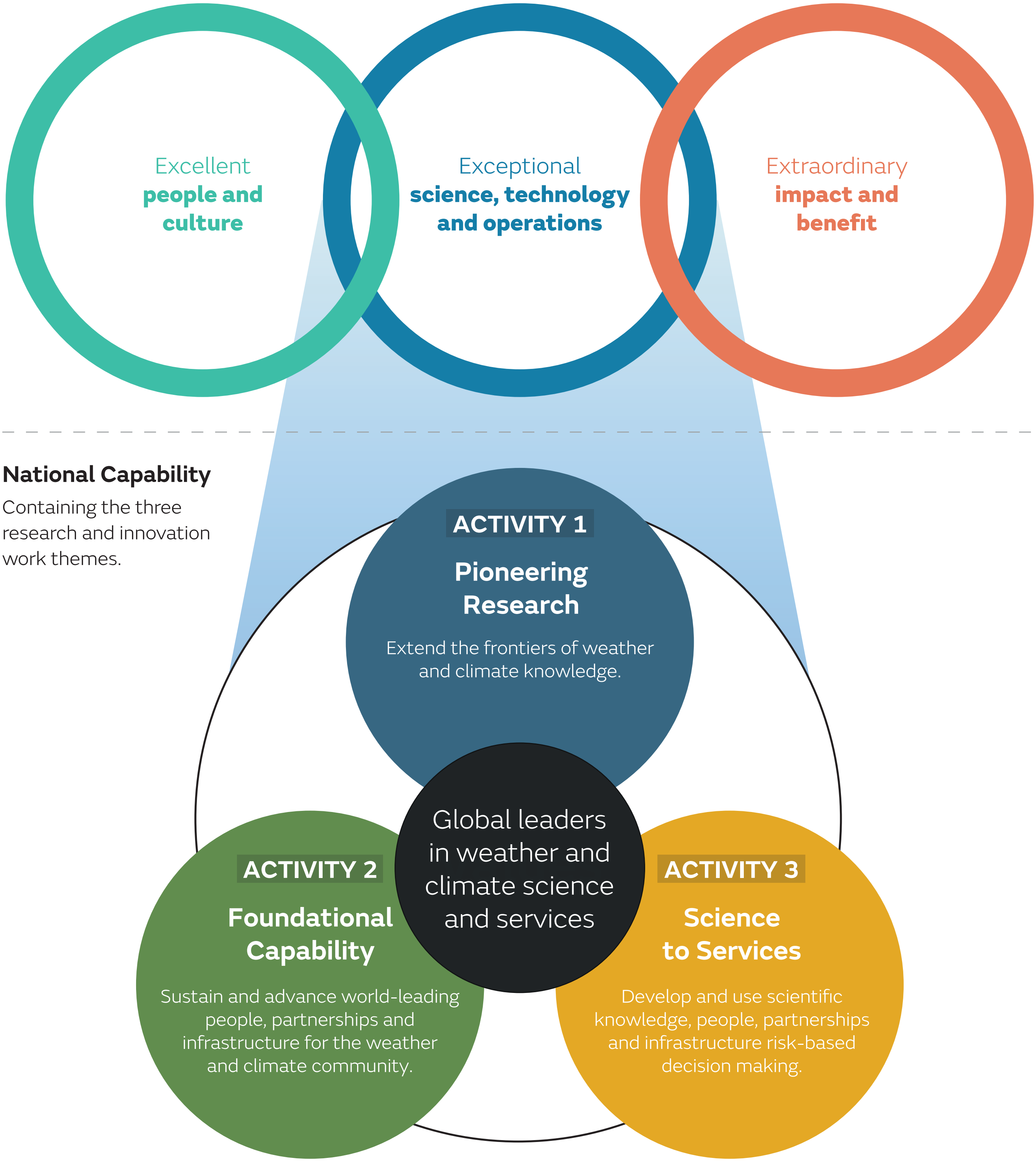


Figure 1 – Met Office Strategy Overview

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. The Impact and Benefit strategy informs our knowledge of the impacts of hazards for our customers to enable their decision-making processes. Drawing on social science expertise we will continue to develop 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. 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. As referenced in the Impact and Benefit strategy, operational meteorologists and climate experts have a pivotal role in analysing and interpreting our data.

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 an 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. In 2022, provision of timely and accurate weather warnings for the named storms Dudley, Eunice, and Franklin demonstrated how the Met Office continues to be a trusted source of information and guidance to mitigate such events.

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, and ways to manage, 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. Both, Met Office science and our scientists continue to play a pivotal role in compiling such evidence for the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report. Our contribution draws on the breadth of the UK's climate expertise and our partnerships with research establishments across the UK and internationally.

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. This commitment was reaffirmed in the Glasgow Pact at COP26 in 2021. 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 our progress to net zero, the climate response, including unexpected changes, tipping points and potentially irreversible changes to our environment, and our progress in adapting to changing climate.

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 observations and 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. The UK has invested in technology and infrastructure to provide strategic advantage, much of which is weather sensitive. As referenced in our Impact and Benefit strategy, 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.

And so, 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, to ensure seamless end to end emergency response.

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.

As referenced in the Impact and Benefit strategy, the drive 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, observations 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, climate science and operations require social science, data science, engineering, and technology. Again, this will increasingly mean the Met Office's expertise and multi-discipline partnerships will be of utmost importance if we are to deliver on the goals of this Research and Innovation Strategy, support the Met Office's capabilities and be prepared for the future.

A recent example is the launch of the UK National Climate Science Partnership, this new alliance between the Met Office and 7 NERC research centres will involve working alongside universities and public and private sector organisations to develop climate solutions to respond to the threats posed by a rapidly changing climate.

Another is through The Joint Centre for Excellence in Environmental Intelligence (JCEEI), a partnership between the Met Office and the University of Exeter. The JCEEI'S Climate Impacts, Mitigation, Adaption and Resilience (CLIMAR) Framework uses Data Science and AI to integrate multiple sources of data to quantify and visualise the risks of climate change on populations, infrastructure and the economy. Examples of the use of the framework include working with a consortium led by the National Digital Twin Programme and the Centre for Digital Built Britain to assess the future risks of flooding on critical infrastructure.

Introducing our National Capability

Weather and climate is big science, requiring large numbers of observations and data, large scale software and large-scale compute and storage. And so, the UK requires a weather and climate National Capability. The weather and climate National Capability encompasses the science and technology required to deliver the data which underpins weather and climate services.

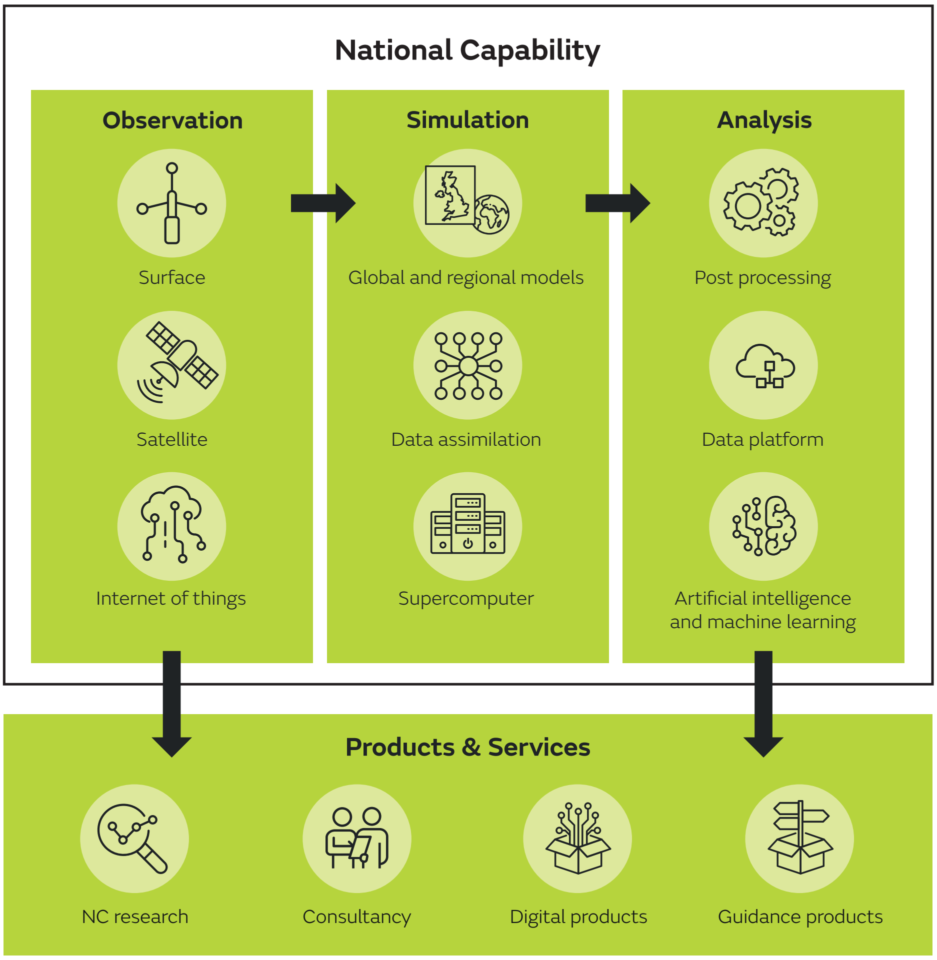


Figure 2 – National Capability Overview

This schematic reflects the weather and climate National Capability and consists of:

- Observations of the Earth system;
- the software and hardware for Simulation of weather and climate; and
- post-processing and data platforms for Analysis into weather and climate information. This refreshed Research and Innovation Strategy recognises the fundamental role of the Analysis capability, allowing us to integrate with other domain data platforms and 3rd party data to better exploit data sciences and advance the Met Office purpose to 'help you make better decisions to stay safe and thrive.'

The weather and climate National Capability allows the UK to deliver world-leading weather and climate science and services, support national strategic needs, and respond to emergencies. As such the weather and climate National Capability consists of the infrastructure to run weather and climate services, as well as the research and innovation to grow and transform the National Capability. This definition of National Capability is deliberately aligned with the UKRI definition because it is delivered in partnership with the UKRI academic community. The Met Office plays a leadership role in running and growing this National Capability. The research and innovation required to transform the National Capability is developed in strong partnership with the UKRI research community.

Transforming our National Capability

To transform our National Capability there are three core workstreams and eleven Research and Innovation themes. 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.

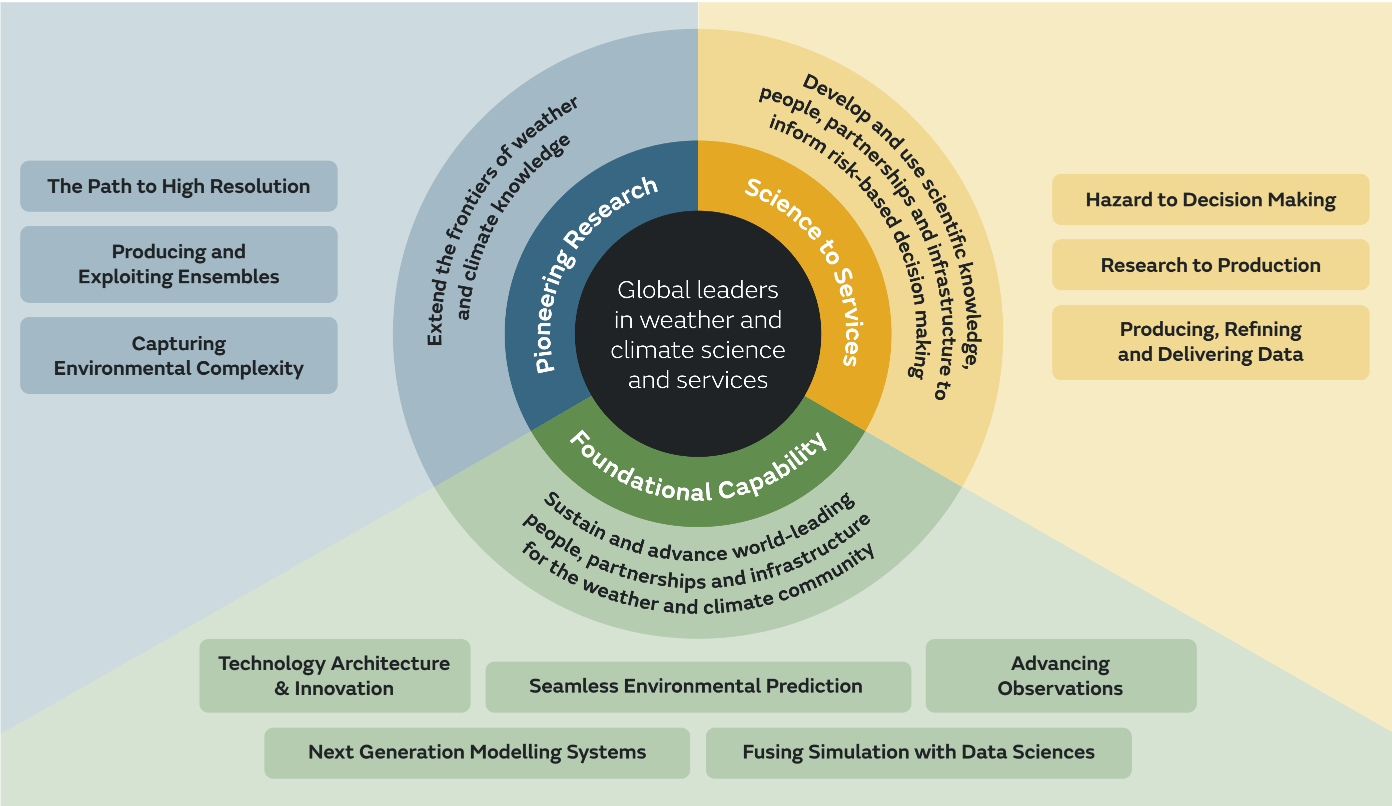


Figure 3 – R&I Strategy Themes

Foundational Capability

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

Our vision for 2030

We shall have transformed the weather and climate National Capability by deploying transformative technologies, such as Digital Twins, to bring together observations, simulation, and AI on cloud-based compute and storage with a reforecasting capability , to allow users to extract greater value from our ensemble predictions.

Advancing Observations

Deliver a step change in our observational capability to close the capability gap, realising the value of third party and opportunistic observations to address our growing needs.

Technology Architecture & Innovation

Big Science demands Big Infrastructure which must be carefully designed and managed to exploit emerging technologies and provide the platform for world-leading research, operations and services.

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.

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.

Fusing Simulation with Data Sciences

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

Science to Services

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

Our vision for 2030

Our data will have moved beyond forecasting future weather and climate to informing action to manage and reduce risks by informing better decision making, across timescales at kilometre scales with ensembles at the heart of all we do.

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 services to meet the future needs of the Met Office and its customers and ensure that users of these services are ready for the impacts of these developments.

Producing, Refining and Delivering Data

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

Pioneering Research

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

Our vision for 2030

Through partnership, we shall have developed the science needed for mature k-scale global simulation, integrated modelling of the water, air quality and the carbon and nitrogen cycles, and have a seamless view of generating relevant and useable ensembles.

The Path to High Resolution

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

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

Capturing Environmental Complexity

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.

Cross-cutting themes

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

As referenced through our Excellent People and Culture anchor and the People strategy, talented and driven people will be at the heart of delivering our ambitious agenda. 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 defines commitment to lead and invest in our people and culture to make the Met Office a great place to a work.

Partnerships

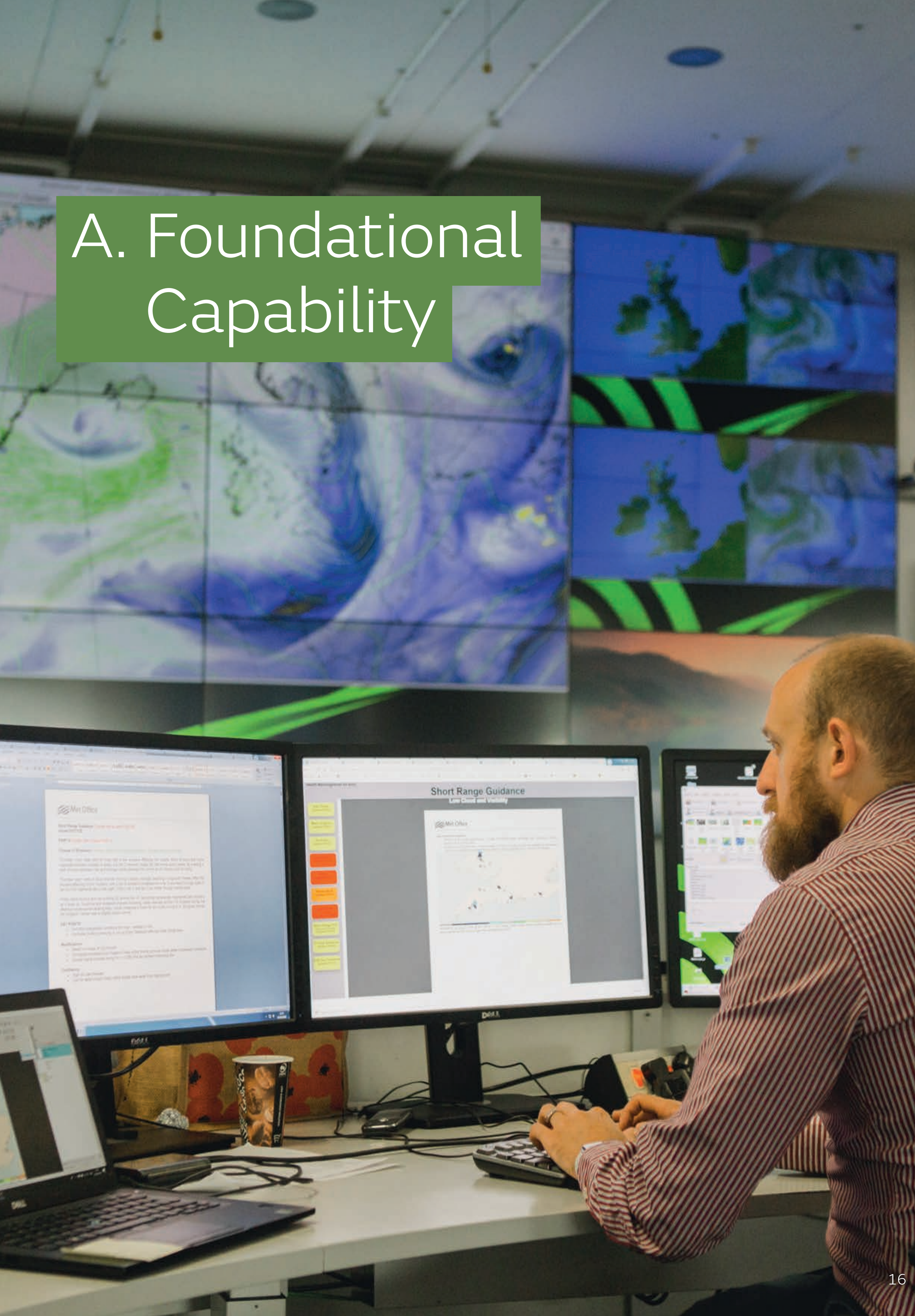
This strategy demands an increase in the range of skills and expertise we shall need to bring to bear, and so working in partnership will become more important than ever before. We shall develop and nurture our existing partnerships, within the weather and climate domain, in universities, national research centres, ECMWF and other national met services, as well as with our technology partners in the commercial arena and international data standards bodies. 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 takes 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, the standards we adopt, or the technology 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.

Appendices

A. Foundational Capability



A.1 Advancing Observations

Observations underpin the pioneering research and science for services at the Met Office and are a key component of the National Capability. They are used to inform understanding of current weather and climate, initialise numerical weather prediction and climate models, verify forecasts, maintain records of climate, and improve models through better understanding of environmental processes. The meteorological community's success in building the Global Observing System (GOS) remains one of the major achievements of international science and is essential to the Met Office. There remains, however, significant weaknesses in coverage, and gaps have widened over recent years as observational requirements have grown faster than advances in observing systems have been unable to match, particularly for applications requiring detailed observational information over the UK. Since it typically takes 5-10 years to deliver benefits from new observational capabilities, a step change is needed now to meet our needs by the 2030's.

Met Office will need to continue to invest research effort in understanding and prioritising observational needs, developing and evaluating new capabilities and exploring new methodologies for exploiting observational data. Informed by this knowledge, we will strengthen our national observations networks and work to address weaknesses in the Global Observing System through proactive engagement in the national and international groups that shape, define and deliver the GOS. We will bring leadership when appropriate, our primary aim remaining to build the most capable composite observing system possible, to serve our global, regional, and national needs. We will seek to adopt the most efficient implementation mechanisms and procurement models available whilst adhering to the WMO Integrated Global Observing System (WIGOS) Network Design Principles to which all WMO Members are committed, proactively supporting initiatives that promote enhanced data exchange. Our observations R&I work will span a range of activities. These will include delivery of additional observations to enable new Supercomputer Programme benefits (including the supply of additional atmospheric humidity measurements, particularly to support high-resolution NWP, and 3-dimensional wind and temperature data globally) and establishing capabilities to make available and exploit data from next generation EUMETSAT satellite missions (MTG and Metop-SG). These will include data from new instruments including the MTG Lightning Imager, Infra-Red Sounder (providing atmospheric temperature, humidity, and wind information in support of high-resolution NWP and nowcasting) and the Ultra-Violet Sounder (supporting the monitoring of air quality and other aspects of atmospheric composition). Whilst these and other planned activities will help to address some of our highest priority observational needs, significant capability gaps will remain, particularly in two critical areas: global climate and fine-scale weather observations (Fig. 4). The need for improved climate change monitoring and prediction is driving us towards more complex Earth System Modelling, which in turn requires observations of a growing range of geophysical variables. Meanwhile, as our society becomes more exposed to environmental impacts, we are investing in forecasting enhancements that can better predict localised, high impact weather events especially in highly populated urban areas. We need corresponding fine scale observations to enable us to observe and understand these events (strengthening situational awareness) and validate the sub-km scale NWP models needed to forecast them.

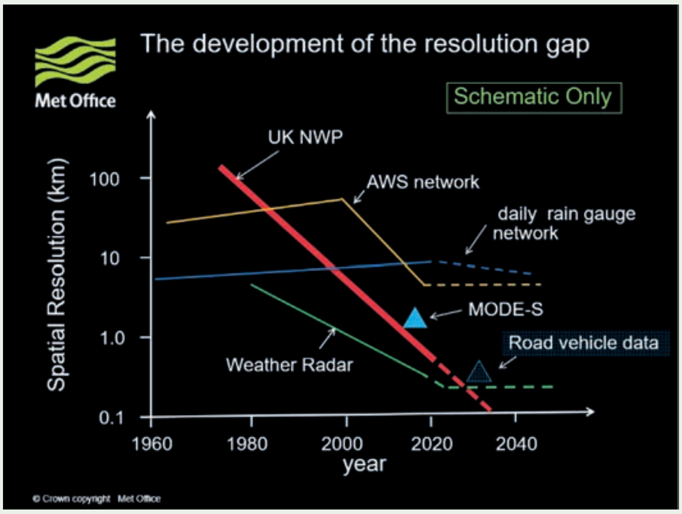


Figure 4 – Schematic illustrating Met Office NWP vs observation network resolution. This shows that model resolution has now largely overtaken our ability to observe the environment. It illustrates the evolution of key observing capabilities. Mode-S aircraft data and Road Vehicles Data are included to show the anticipated contribution from these new/potential networks.

[1] 'Manual of the WMO Integrated Observing System', Annex VIII to the WMO Technical Regulations, 2019 Edition updated in 2021, WMO-No 1160.

Accessing these data can be a significant challenge, so we must also work in partnership with government sponsors, regulators and industry to develop systemic solutions to tackling this issue. Our overarching aim must be to significantly accelerate the pull through of new capability into operations and wider use across the Met Office at an affordable cost.

Goal 1

Deliver a step change in our observational capability to close the most pressing capability gaps, realising the value of third party and opportunistic observations to address the growing need for fine-scale weather observations.

Goal 2

Further enhance global observations for weather and climate applications through our contributions supporting and implementing the WIGOS Vision, the WMO Data Policy and associated activities.

To achieve this vision by 2030 we aim to:

1. Continue to sustain and maximise the exploitation of the underpinning reference and baseline networks, seeking efficiencies for reinvestment where possible;
2. Continue to proactively engage in the national and international groups that shape, define and deliver the Global Observing System;
3. Pull through the benefits of our investments in new capabilities, particularly next generation satellite missions, that will become available on the timescales of this R&I Strategy;
4. Work with government agencies to raise awareness of our observational challenges, with a view to co-creating suitable funding opportunities for UK academia;
5. Focus new efforts on our existing and new academic partnerships to identify opportunities to assess low Technology Readiness Level observational opportunities for viability;
6. Work with government agencies, industry, and international partners to systemically enable access to greater volumes of observational data, including non-traditional and 3rd party data;
7. Identify and work with other partners to develop methodologies to exploit existing and novel observations data and implement these operationally and across other activities;
8. Implement scalable, agile, cloud-based data management infrastructures, defining and adopting common standards to ensure interoperability with partners and exploiting new tools and methods to accelerate implementation and collaborative working.

Case study

Forecasting urban scale impacts and the role of observations

The ambition to forecast weather and advance our understanding of the changing climate on the urban scale implies the development of a completely new observations capability. The immediate need is for specialised observation campaigns to support model development, but any future forecast services will require high resolution observations to, i) Enable the verification of the much higher resolution forecasts and ii) Provide situational awareness, to support nowcasting and future forecasting requirements, including the observation of impacts. For model development, deployment of specialised research instruments in field experiments designed to provide detailed constraints for process-level assessment are needed. Fine-scale observations including from the FAAM research aircraft and Cardington boundary layer facilities will focus on key phenomena including convection, urban meteorology, surface-atmosphere exchange, and stable boundary layers. Research experiments will build on strong existing national and international partnerships.

Currently, when considering our existing, dedicated meteorological networks, only the weather radars and some satellite imagery can resolve atmospheric structure on the km scale, and severe weather on this scale is either completely undetected, or not detected reliably. Several academic institutions have created sensor networks in urban areas that could be integrated into our networks. Further enhancements could be achieved by new remote sensing instruments developed collaboratively to exploit emerging mass-market technologies. However, to fulfil the bulk of the requirement for high-volume/low-cost urban scale observations, we will be heavily reliant upon opportunistic data. We have already demonstrated how such sources can provide observations at the ~few km scale, showing the potential of opportunistic networks. Examples include Mode-S aircraft data and amateur weather station data. Included amongst the most promising future opportunities are the sensors on the rapidly increasing numbers of 'connected' road vehicles, the future emergence of large commercial drone fleets, and the opportunistic use of wireless communication networks.

A.2 Technology Architecture & Innovation

The development of ideas within observations, weather, and climate sciences relies upon an underlying ‘technology platform’. It enables and empowers research activities and is vital to the delivery of value to the customers – moving ideas from ‘science to impact’.

The Met Office undertakes pioneering research, applies this science in modelling and prediction and operates those models to afford better decision making. In each of the areas of research, development and operations, the underpinning platform is vital.

To leverage benefit from of these and other technological advances, the Met Office will use a ‘platform’ approach to ensure that we are identifying and adopting the best technologies. We will also develop our people and establish the practices necessary to maintain a position at the cutting-edge in all areas. The Met Office will develop the coherent design and architecture needed to achieve these objectives, ensuring that full, holistic research to outcomes value streams are designed and maintained.

In addition to a focus on the Research and Innovation environment, this approach brings additional benefits including: enhanced resilience opportunities through substitutable services and reduced operational overheads by having shared platforms which support research, development and operations.

A platform approach to empower science, research and innovation

We aim to establish a federated cloud data platform to support the National Capability. This will provide a coherent set of services for research, development and operations; tailored to meet the needs of each domain yet designed to enable simple pull through from research into operations. Services will span from provisioning compute resources within the HPC environment, to cloud-based object storage, to data discovery and retrieval, and to high-level functions such as interpolation and site-specific derivation used in post-processing applications.

Adopting this platform enables and empowers domain workers as:

- Enables scientists and engineers to focus on domain problems rather than technology infrastructure
- Reduces the barriers to moving ideas from research through development and operations by providing a coherent set of services across these differing environments
- Simplifies access to and exploitation of new platforms with reduced overhead – for example, European Weather Cloud (EWC) or future digital twin clouds
- Creates opportunities to trial and adopt new technologies as they become available on 3rd-party platforms

Goal

Using a cloud-based and decentralised (federated) data platform, create a coherent set of services to support the National Capability.

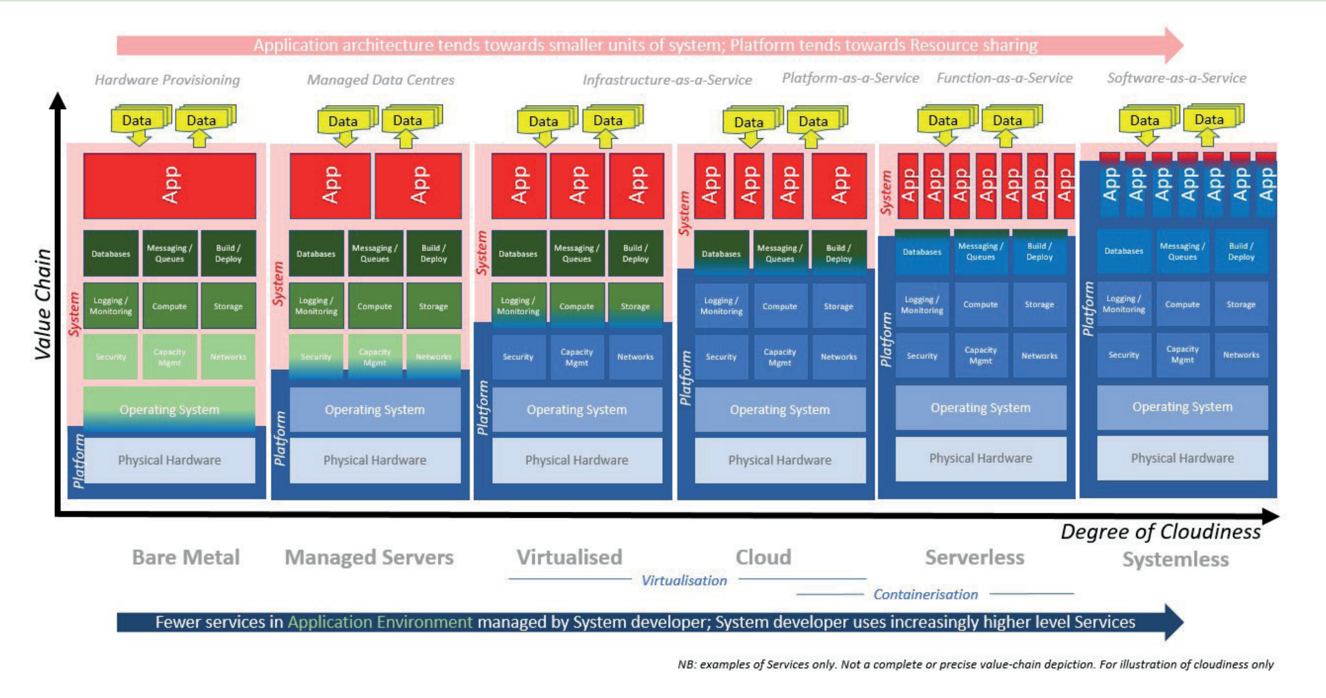
To achieve this, we will:

1. Invest in up-front architecture, design and assurance of the services and platforms we need;
2. Work with partners and collaborators to build a platform that supports National Capability from research, through development to operations;
3. Collaborate with commercial, national, and NGO cloud providers to develop standards for data and cloud service interoperability;
4. Develop the high-level platform service model for weather and climate domain users;
5. Migrate domain users to utilising services with ever greater degrees of abstraction from the underlying technology infrastructure.

What is a Platform?

A platform supports multiple independent user-defined systems through unified access to the high-level services of an integrated set of shared capabilities. Platforms enable user resources to be focused on the domain-specific problem rather than the infrastructure to operate a solution by moving operational overheads and non-functional responsibilities for the integrated capabilities from the platform user to the platform providers.

Platforms range from 'bare metal' services of basic hardware resources to high-level application-specific services at the systemless end of what the Met Office terms the 'degree of cloudiness'.



Higher degrees of cloudiness reduce the amount of time and resources expended by domain experts on the overhead work of building and maintaining an application context of services need for the application – which is where the value creation happens.

What is a Federated Cloud Data Platform?

Adopting this perspective on the services available to the Met Office staff and our collaboration partners enables us to have a single model which encompasses not only Met Office capabilities, such as the HPC and MASS storage systems, but also the increasing number of external opportunities presented by commercial cloud offerings, private and community clouds such as the European Weather Cloud, and emerging 'digital twin' initiatives.

This leads to a need for effort to be focussed on federating platform services across multiple platforms – both intra- and inter-organisation - with the emphasis being on the capture, storage, processing, analysis, and visualisation of the types of data used in weather and climate. The goal is not to create a Met Office specific cloud federation mechanism but to collaborate with commercial, national, and NGO cloud providers to develop appropriate standards for data and service interoperability.

Technology-driven innovation

We will leverage and benefit from the research activities of technology institutes and vendors through a strategy for technology-driven innovation.

Technology-driven innovation requires the monitoring and awareness of technology trends, engagement with institutes and vendors, and the translation and collaborative development of ideas with domain experts.

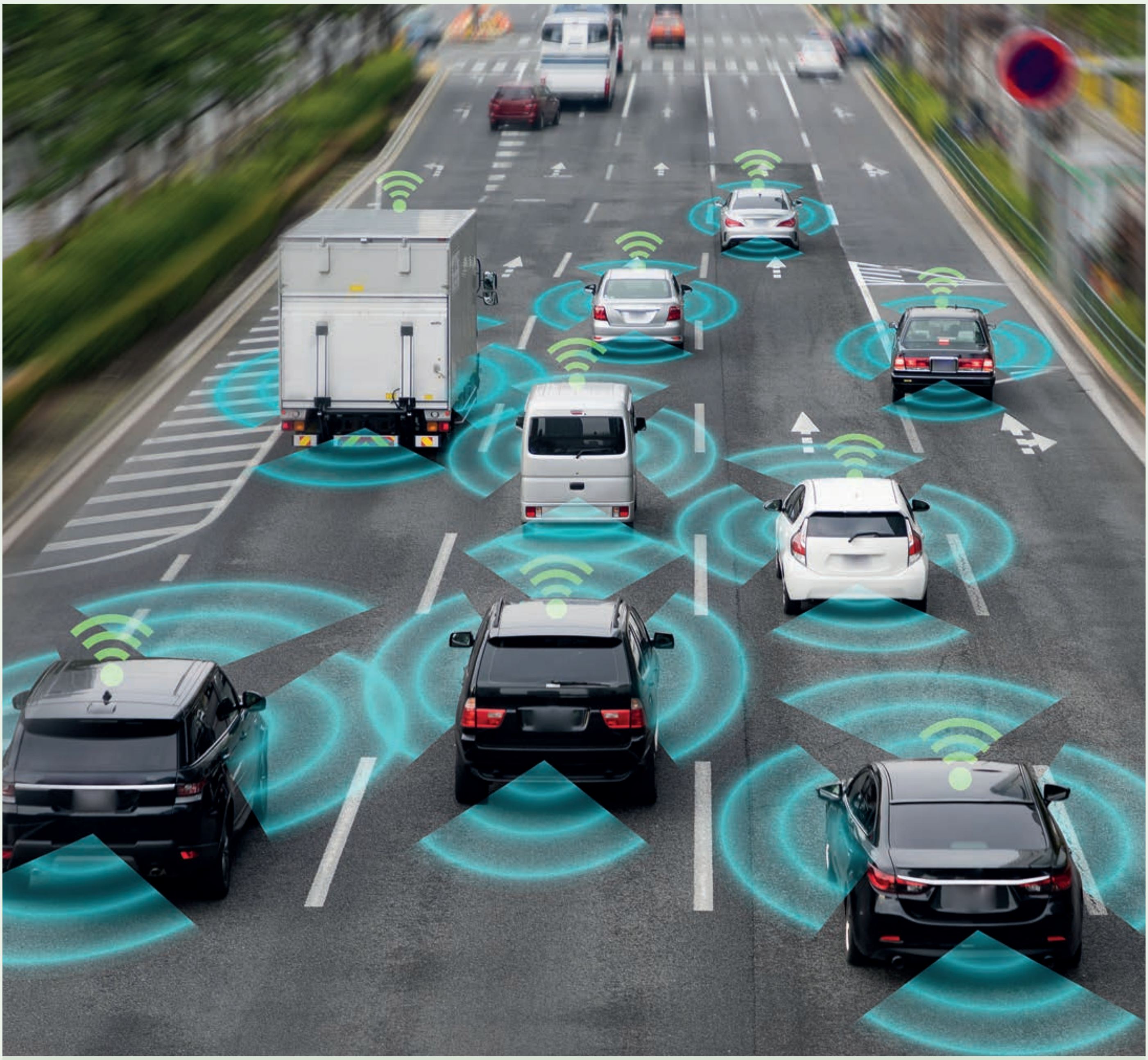
In addition, innovation only succeeds when new ideas are delivered and add value for users or customers. New technologies can be disruptive, so there needs to be an effective process from ideation through to adoption which takes in account not only the application of the technology but it's operation and impacts on people - ways of working, skills, and practices.

Goal

To have an effective practise of technology-driven innovation that will bring new ideas into the awareness of the domain experts – transforming their work into operations and delivering value to customers

To achieve this, we will:

1. Establish a capability for continuous technology trend monitoring, assessment, and a briefing programme for Met Office staff;
2. Establish practices for monitoring and encouraging emergent internal technology-driven innovation – this includes operating community forums for sharing ideas; recognising and championing early ideation efforts into trials; and, guiding trial-to-adoption opportunities;
3. Create capacity for hands-on assessments and implementations of key new technologies, going beyond basic proof-of-concept initiatives – these emphasise ways-of-working, feasibility, and viability as well as desirability;
4. Actively lifecycle our technology portfolio by driving utilisation after adoption and retiring previous generations of technology.



Technology trends for technology-driven innovation

Technology Trends are important because they represent where the most investment and development activity are being undertaken in the market, which largely determines what the technology landscape will be - where we, our partners, our customers, and competitors will be operating in the future. Technology Trends are not always the coolest or newest things but are the things which have the biggest implications and impacts.

Technology Trends are primarily defined by industry analysts and pundits, but they often emerge from communities who are active on the edge of technology research and innovation. As such it is necessary to not only monitor the analysts and pundits but to engage with technology research organisations and communities – firstly, to spot and be aware of new trends, but also to help define and promote trends we see as being of benefit to our work. In this way, we are not only passive observers of trends but active participants and influencers of trends which are of benefit to ourselves, partners, and customers.

We will develop a classification approach that will focus our resources on the most significant trends. Not all trends are relevant or of significant importance to the Met Office context, but it is important to understand them as they will be affecting the contexts in which our suppliers, partners and customers are operating.

A.3 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 HPC (High-Performance Computing) architectures is changing dramatically, as physical constraints on micro[1]electronics mean that future increases in the speed of computation will place significant demands on the flexibility, adaptability, and scalability of our codes.

Therefore, 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 HPC platforms of the future. This transformation of our model structures will also provide many exciting new 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 high-performance computing platforms.

To achieve this goal by 2030 we aim to have:

1. Weather and climate research and prediction systems that are designed for future generations of high-performance computing platforms, unlocking new scientific potential.
2. An end-to-end modelling system, from observations through simulation to model output, which is future-proofed to changing high-performance computing platform 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 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.

Figure 5 - 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.

A.4 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 goal 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. Build 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 data sets and innovative use of model/ensemble datasets. This will inform delivery of Science to Service through the Research to Production and Hazard to Decision Making themes.

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;
- Work with the Research to Production theme to 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.

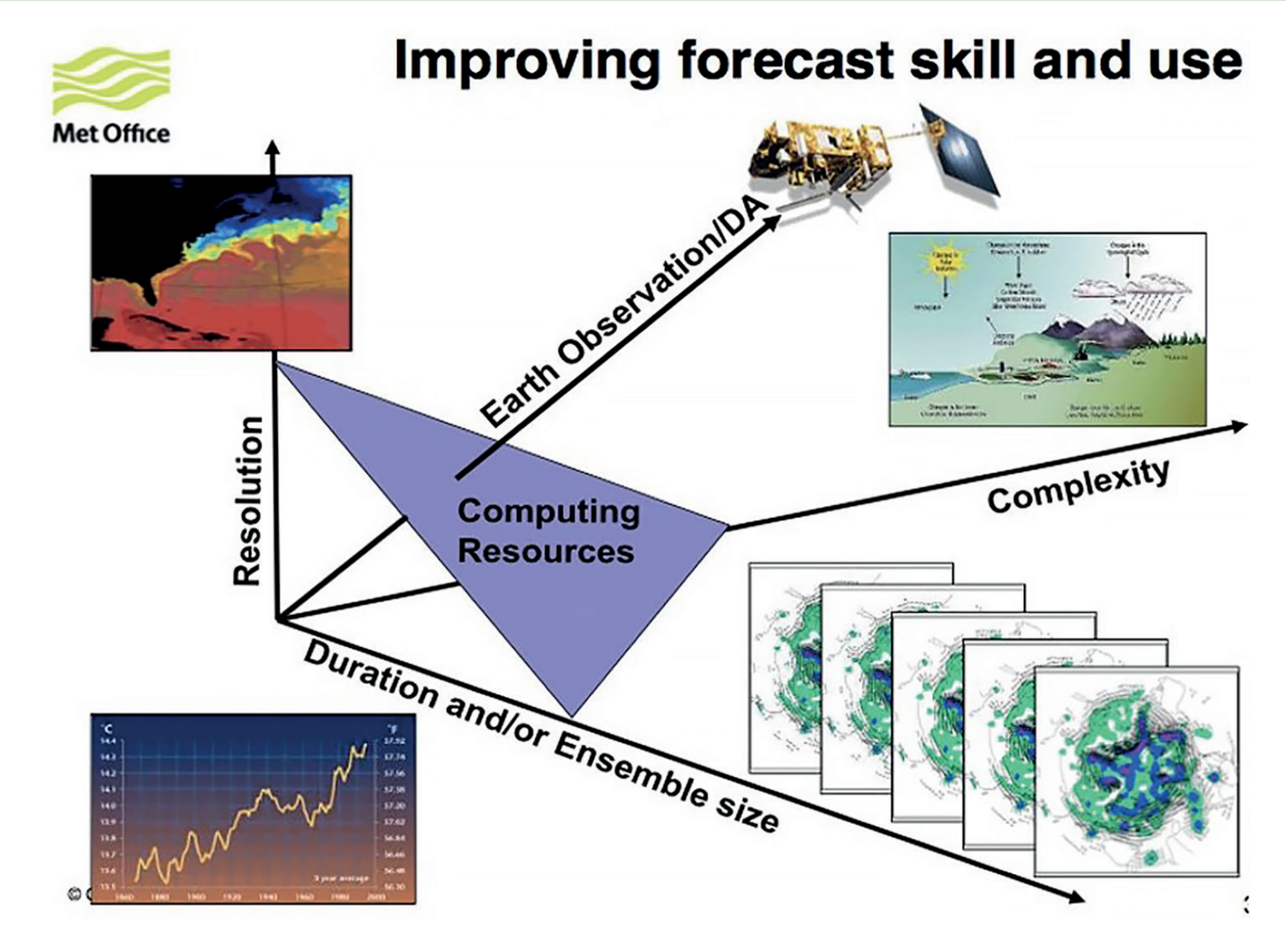


Figure 6 - A schematic illustration of the competing factors for computing and human resources to deliver improved predictions and projections across timescales.

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 10km and no parametrized convection at 4km and higher resolutions. This convective "grey zone" where convection is partially resolved applies across grid spacings ranging from approximately 100m 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.

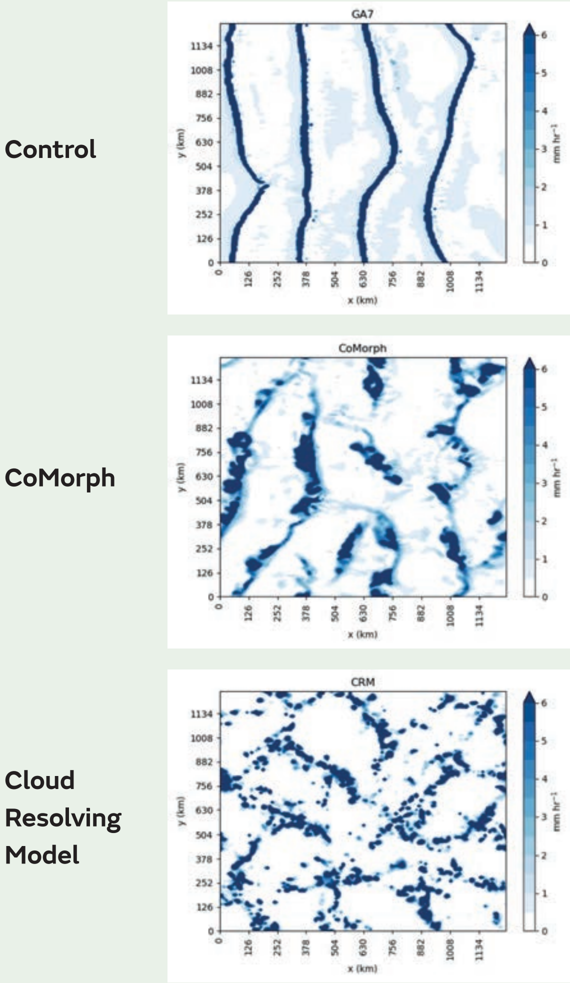


Figure 7 - Surface rain rates in idealised model experiments. These allow us to investigate the behaviour of convection parametrization schemes in a controlled environment. Top: The control convection scheme currently operational in the UM, Middle: a prototype of the new CoMorph scheme, Bottom: a cloud resolving reference simulation at 1 km resolution. The structures within the new scheme better resemble their higher-resolution counterparts.

A.5 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 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

To harness the power of Data Sciences to push the frontiers of weather and climate science and services.

The Data Sciences Strategic Framework 2022-2027 outlines how we will achieve our goal. Arranged under the three pillars of capabilities, people and partners, it presents activities that develop, support and maintain an enabling environment wherein the use of Data Sciences in the weather and climate endeavour can thrive.

To achieve this goal by 2030 we aim to have:

1. Capabilities – the first pillar within the Data Sciences Strategic Framework identifies capabilities that are needed to ensure they can be deployed to respond to a dynamic and fast-evolving environment.
2. People – the second pillar describes how an enabling environment will be created that attracts, retains, and develops the skilled workforce needed to realize our Data Science ambitions.
3. Partners – the third pillar describes how we will work with partners across the national and international community to deliver more than the sum of our parts.

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.

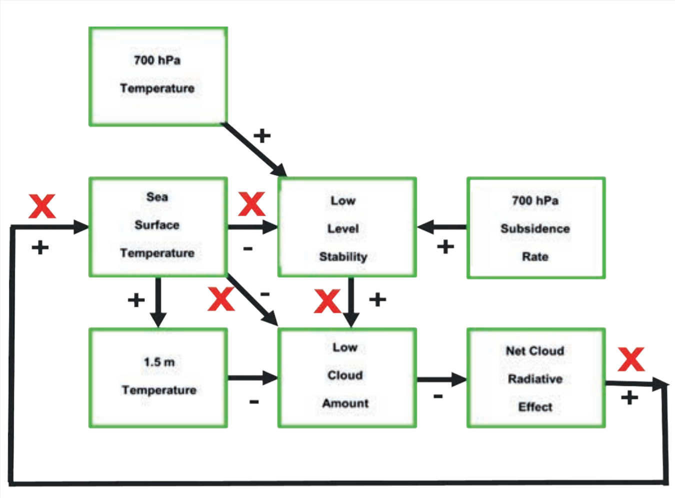


Figure 8 - Relationships between subtropical low cloud and cloud controlling factors in observations are shown by arrows, and the signs indicate the sign of covariation. The current version of the climate model captures many of these relationships but some are weaker than observed (red x symbols). Insights from this work can be used to improve relationships between clouds and cloud controlling factors in future versions of the climate model.

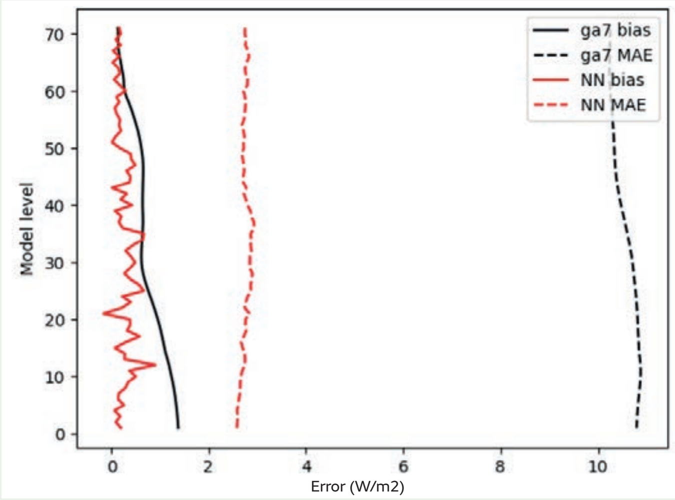


Figure 9 - Vertical profiles of errors in shortwave radiation from a machine learning approach (a deep neural net emulator, NN) and a traditional parametrization scheme (the current GA7 scheme). The errors shown are the bias (solid) and mean absolute error (MAE, dashed) and are relative to a high spectral resolution benchmark. The machine learning approach provides a more accurate prediction.

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.

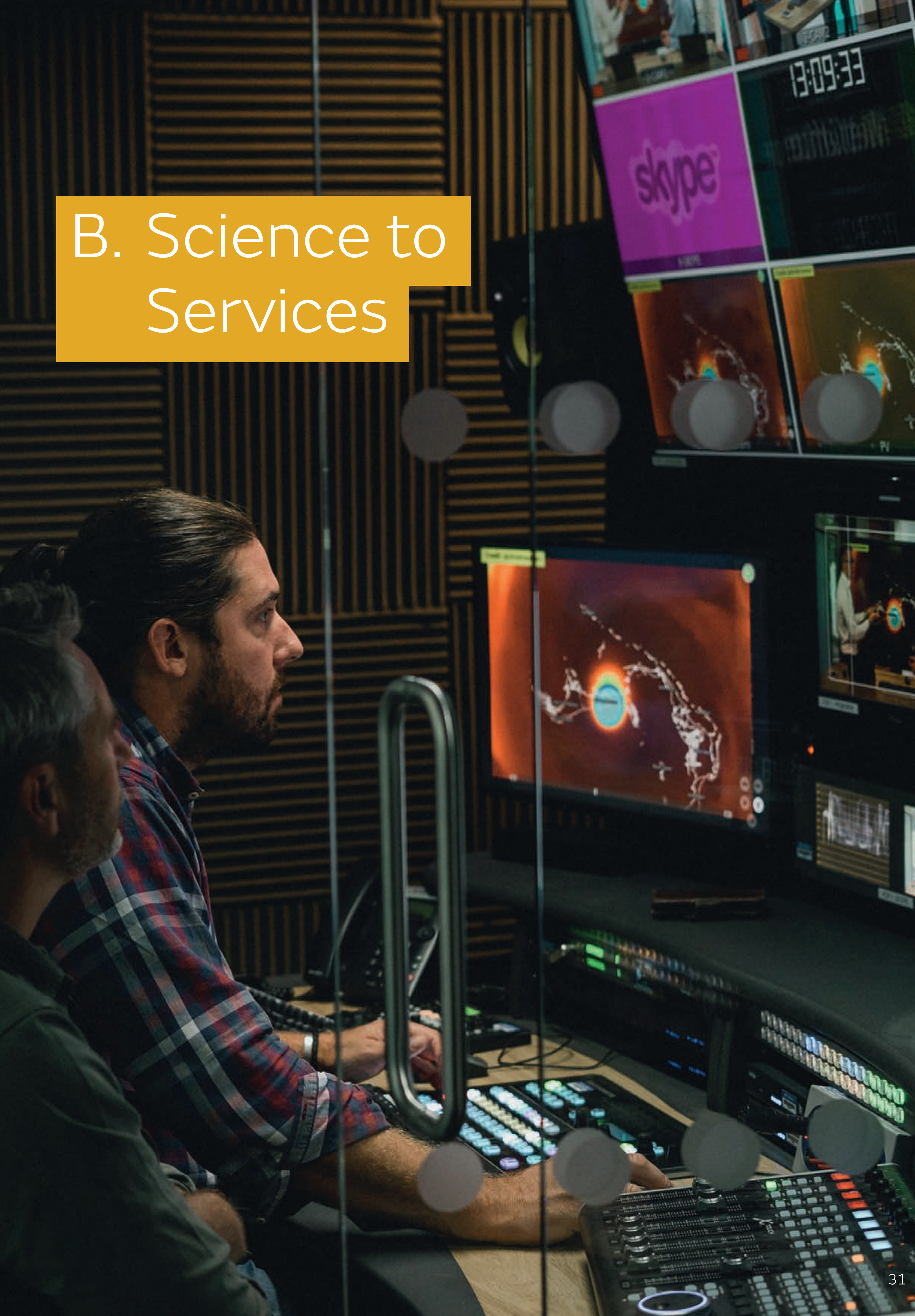
We can use SOMs to investigate relationships between clouds and cloud-controlling factors in observations and climate model simulations of the low-level stratocumulus deck off the coast of California. SOMs detect strong relationships between variables that are missed or only weakly detected by linear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

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 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 optimized 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 minimize computational cost or maximize accuracy.

B. Science to Services



B.1 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.

The impact areas we will focus on include:

- Wind, snow, ice, surface flooding, heat stress
- Landslides, coastal erosion, 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

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 goal 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.

Case studies

Figure 10 - 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.

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.

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 minimized, 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.

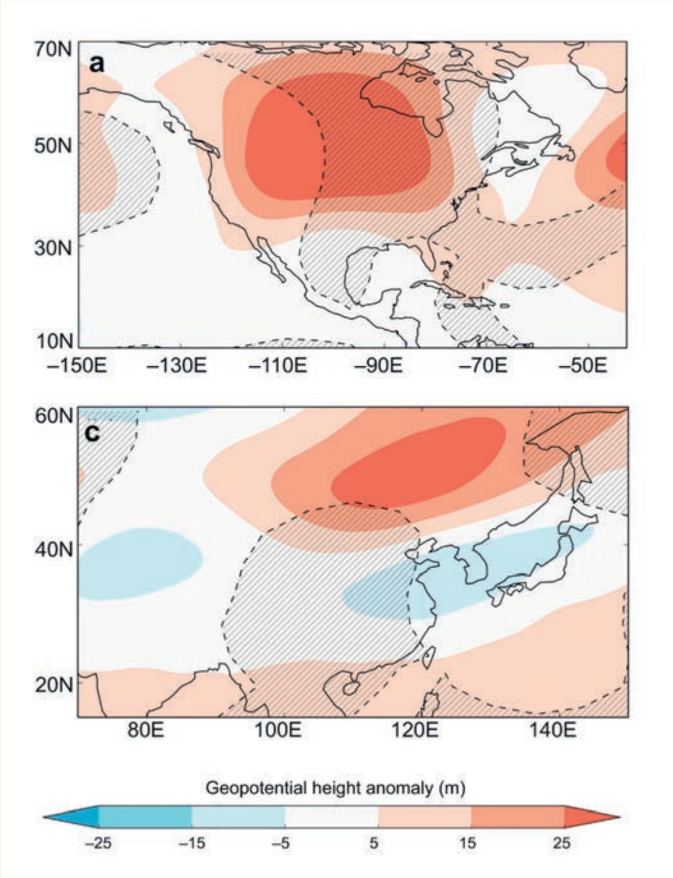


Figure 11 - Plausible, but unprecedented June-July-August conditions associated with national-scale severe water stress events which would threaten maize crops over North America and Asia. The colour shading shows the 200 hPa geopotential height anomalies. Red areas indicate areas of higher than average values –these conditions are associated with dry conditions which would severely impact maize yields.

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.

B.2 Research to Production

Over the next decade, our Pioneering Research themes will deliver improved insight and environmental modelling capabilities, and our Foundational Capability themes will enhance our ability to exploit these efficiently. To translate these developments into world-class modelling systems we must understand the benefits these will bring and how these will meet both user and customer requirements.

With the increased sophistication of weather and climate modelling, the transition of research into operational systems becomes increasingly costly and challenging. On weather forecasting timescales, we must maximise the value of these systems to operational meteorologists so that they can provide the best advice to our customers. We must also maintain and improve the quality of our automated products so that these remain world-leading in a competitive market. To achieve these goals will increasingly require researchers, developers and operational users to work together to ensure that our tools, techniques, products and services are fit for the future.

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 was due to greenhouse gas emissions. Consequently, the operational requirements of climate models have moved from the qualitative to the quantitative. The Paris agreement established stringent targets and our progress against these targets require quantitative assessment; this commitment was reaffirmed in the Glasgow Pact at COP26 in 2021.

Goal

Pull through developments in weather and climate research to improve our services to meet the future needs of the Met Office and its customers and ensure that users of these services are ready for the impacts of these developments.

To achieve this goal by 2030 we aim to:

1. Develop and life cycle a consolidated, comprehensive national/local-scale nowcasting capability combining novel observations, advanced data blending and temporal integration for the analysis and very short-range prediction (0-2 hours) of routine and hazardous UK weather.
2. Develop and implement a coupled, ensemble-based, relocatable km-scale regional environmental prediction capability and use this to achieve a step-change in UK forecasts of routine and hazardous weather out to 2 days and beyond.
3. Develop and implement a coupled, ensemble-based, 5km-scale global environmental prediction system focussed on routine and hazardous weather out to 7 days and beyond.
4. Develop and implement improved season predictions for the 2–4-month range and beyond.
5. Utilise our WMO designation as Lead Centre for annual-to-decadal prediction to collate, synthesize and deliver state-of-the-art multi-model predictions of near-term climate.
6. Develop and use world-leading, robust, reliable, multi-decadal global and regional climate projection systems that encompass uncertainty for delivering risk-based national UK and global projections. Ensure that these are suitable for assessing greenhouse gas budgets, climate warming targets and future climate hazards for adaptation, as well as for supporting International Policy agreements and exploring cutting-edge research.
7. Develop objective methods to determine the optimal balance between resolution, ensemble size and complexity for these weather and climate systems.
8. Specify and deliver the tools and systems required to allow users to fully exploit model and observational data in downstream applications.
9. Develop new operational approaches to utilise and exploit these data, particularly in the context of fully ensemble-based prediction systems. Investigate how data science can help us understand and improve decision making in operational forecasting.
10. Further develop a collaborative approach between scientists, technologists and operational users (including operational meteorologists) to pull research developments through into operational use and operational insights and requirements back through into research activities and priorities.

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.

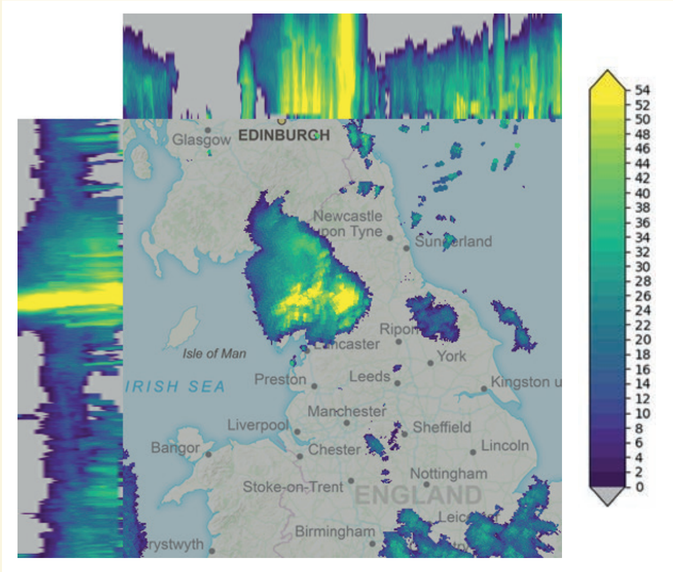


Figure 13 - Three-dimensional radar observations allow the horizontal location and depth of convective cells to be easily identified, enabling better advice and warnings during a severe weather event. This example imagery shows transects through a 3D cube of gridded radar reflectivity (dBZ) on 25th July 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) east-west and (top) north-south planes. In this case, the feature of interest is a supercell, with a cloud top above 12km. This caused wind damage near Hawes and large hail was observed in Northumberland.

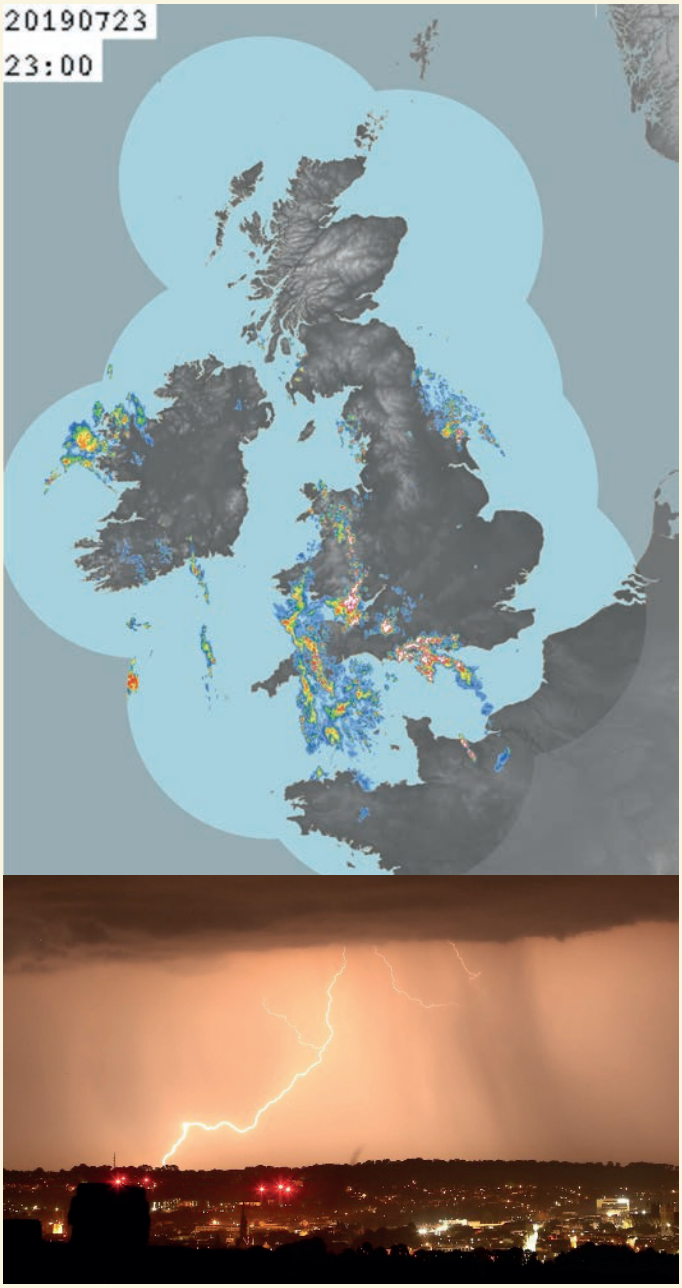


Figure 12 - Radar imagery and accompanying photo of cloud-to-ground lightning strikes over Exeter, Devon, late in the evening on 23rd July 2019. Photo taken by Matt Clark, Met Office.

Testbeds as a vehicle for collaboration between professions

In meteorology, a "testbed" is a period of developmental testing and assessment, often performed in an operational-like environment, in which researchers, developers and users of operational systems can jointly investigate the performance and impact of new capabilities and new ways of working. Participants can collaboratively investigate new models, observations, diagnostics and tools during early stages of development, which can accelerate pull-through into operations by highlighting and addressing any issues and informing users of the benefits and characteristics of new capabilities. Operational users can present researchers with the operational challenges that they face, and participants can collaboratively develop and assess new ways of working to address these challenges.

The "UK testbed project" is assessing the benefits of testbeds for the Met Office and our collaborators. Some initial testbeds have assessed new observational, modelling and diagnostic developments and have investigated and promoted the exploitation of ensemble forecasts and post-processing techniques. This developed useful collaborations between scientists and operational meteorologists and provided new insights into the capabilities assessed. Future testbeds will also assess new operational tools and techniques and include collaboration with technologists, Universities and other meteorological institutions as well as coordination with major observational campaigns.

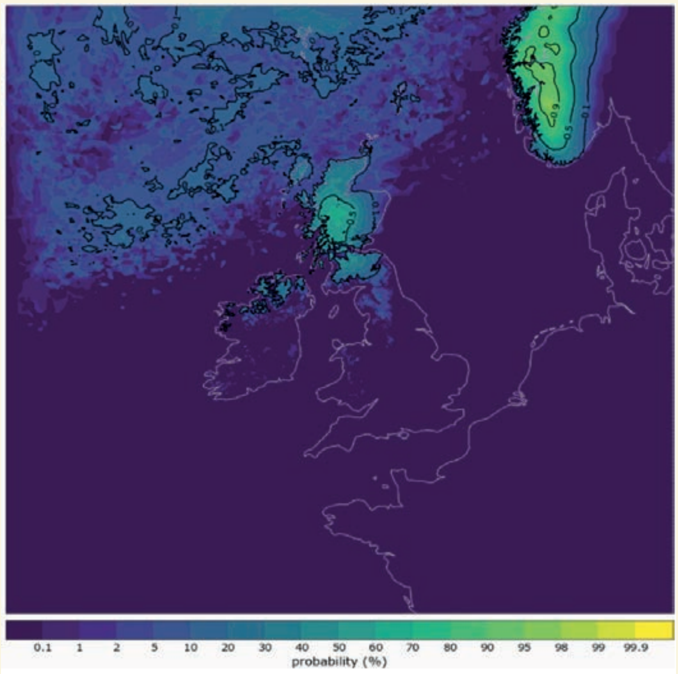


Figure 14 - Probability of snowfall (> 0.1 mm/hour liquid water equivalent) from a 2½-day forecast from the IMPROVER probabilistic post-processing system during February 2022. IMPROVER forecasts were routinely used and assessed during the 2022 winter testbed ahead of its planned operational implementation.

B.3 Producing, Refining and Delivering Data

Data is the lifeblood of everything we do at the Met Office. Delivering impact for users and stakeholders from investment in enhanced capacities for observation and simulation will only happen with corresponding investment in the underpinning platforms capable of managing, processing, and sharing our weather and climate data.

The challenges we face in respect to data are well characterised by the so-called “5 Vs of big data”:

- Volume: faster computers, more complex simulations and new observing platforms all lead to massive increases in the volume of data generated by us and our peers.
- Velocity: observation and simulation data is being generated faster than the rate that we can use or share.
- Variety: earth system modelling and new sources of observations, such as Connected Autonomous Vehicles (CAV) and Internet of Things (IoT) devices, mean that we are working with ever-more diverse types of data.
- Veracity: reliability and trust are essential. Can we guarantee that data will be available when we need it? Can we validate data quality?
- Value: data value is derived from its use - transforming data into value requires both technical infrastructure and enabling policy.

A number of key technologies and approaches will be required to address the 5 Vs to ensure that the right data gets into the hands of those that need it. These range from Cloud-based ‘big data’ platforms that are needed to provide massive data storage with co-located computing resource that can be provisioned on an as-needed basis, to the use of standards such as modern data formats that are required to be optimised to support queries at massive scale, and Web-friendly open-standard APIs provide rich metadata and simple methods to retrieve sub-sets of data, mitigating the need to download entire datasets, and for specialist knowledge about the data structure or how it is stored.

In addition, our Data Strategy Framework defines the governance of data and data services with principles that direct the sharing and use of our observations, guidance, predictions and research data. Within this, data can be categorised to make it easy to understand appropriate usage: research-ready, analysis-ready, decision-ready, and application-ready

Categorisation of data according to appropriate use depends on factors such as the degree to which the data has been validated; it conforms and complies with standards; how much it is shared; the knowledge required to work with it and the guarantee that it has not been interfered with or corrupted.

This categorisation is shown in Figure 15 and enables us to think about the platform used for working with the data, the products and services that can be offered, and the ways of working that are appropriate when operating with this type of data. For example, Application-ready data must be validated so it can be relied upon by thousands (or indeed millions) of people, highly available, timely, externally accessible, and guaranteed not to have been interfered with so that it can be used in critical applications. As such we need the platform to have high levels of service with formal lifecycle management practices in the ways of working for changes to the content and services supplying Application-ready data.

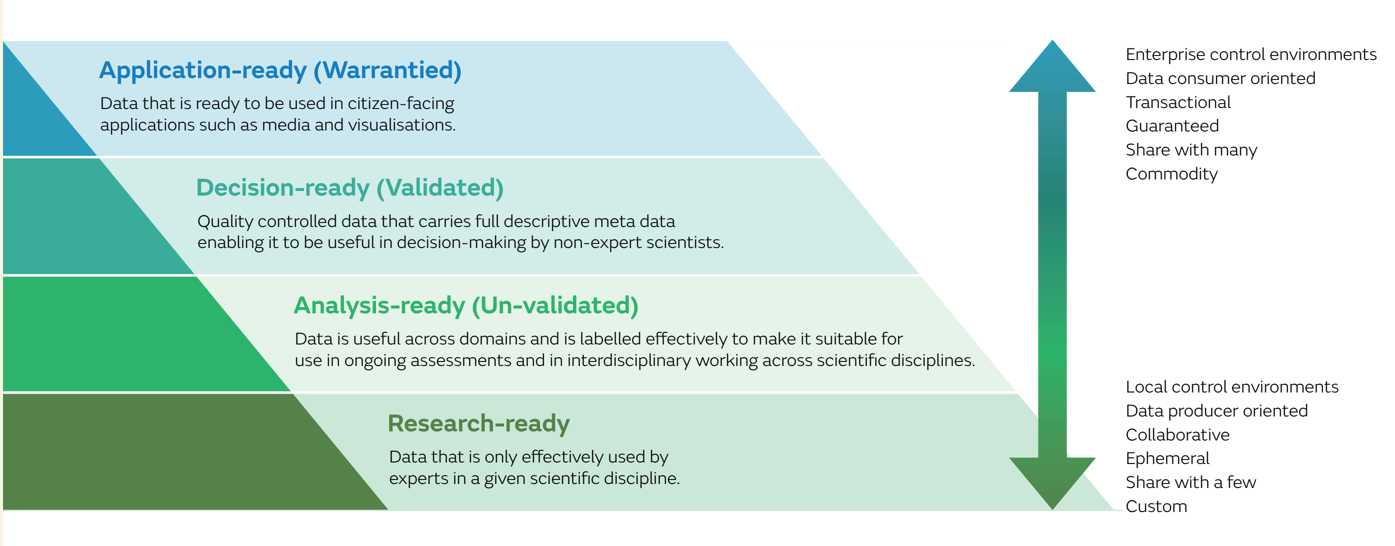


Figure 15 - Categorisation of data according to appropriate use

Goal

To establish the capabilities required to capture and share data from observations and predictions, 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 goal by 2030 we aim to:

1. Establish a federated cloud data platform architecture providing rapid adoption of, and access to, best-in-class processing, analysis, and data management services necessary for our world-leading research and operations.
2. Establish new post-processing frameworks and scientific methods, leveraging the federated cloud data platform and emerging technologies such as ML/AI, to deliver products better suited to the needs of the public, research partners, customers, and other stakeholders, who benefit through our observations, weather, and climate data.
3. Collaborate with vendors and institutions to develop new technical capabilities, data standards, and protocols required to give access to, manage, process, and share the increasingly massive volumes of data we generate and require for our scientific and operational work. For example, we need to stop moving data between platforms and start utilizing querying services and data proximate compute services to tackle the challenges of latency, duplication storage costs, as well as reduce the environmental impacts of the technology infrastructures themselves.
4. 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.
5. Categorise our data according to appropriate use, define clear policies and governance arrangements for each category.

Case study

New Protocols - OGC API - Environmental Data Retrieval (EDR)

Meteorological data is both large and complex and is produced in a wide range of formats, which can make for a steep learning curve for anyone wanting to use it. Traditionally, the use of weather and climate data has been undertaken by a domain-expert scientist or meteorologist but increasingly a wider community of data scientists and web developers want to combine meteorological data with social and economic datasets to determine impact. In the past data access technologies have focused on replicating the functionality that the user would have had if they were accessing the dataset on their desktop. This limited the possible audience and increased the complexity of the technology required to provide the solution.

The custom data interfaces also limited data discovery and usability and making data easier to access is not the same as making it easier to use. A combination of specialist formats and subdomain specific taxonomies can hinder data utilisation, as data consumers interested in values to pass into a decision-making system must have access to the tools and skills required to manipulate each of the data types that they are utilising.

Furthermore, there is a direct link between the number of users consuming a data service the difficulties in improving the data and technologies providing it. Major changes cannot be made until most of the data users have updated their systems, the delays this can cause limit innovation and data improvements whilst increasing service costs due to duplication.

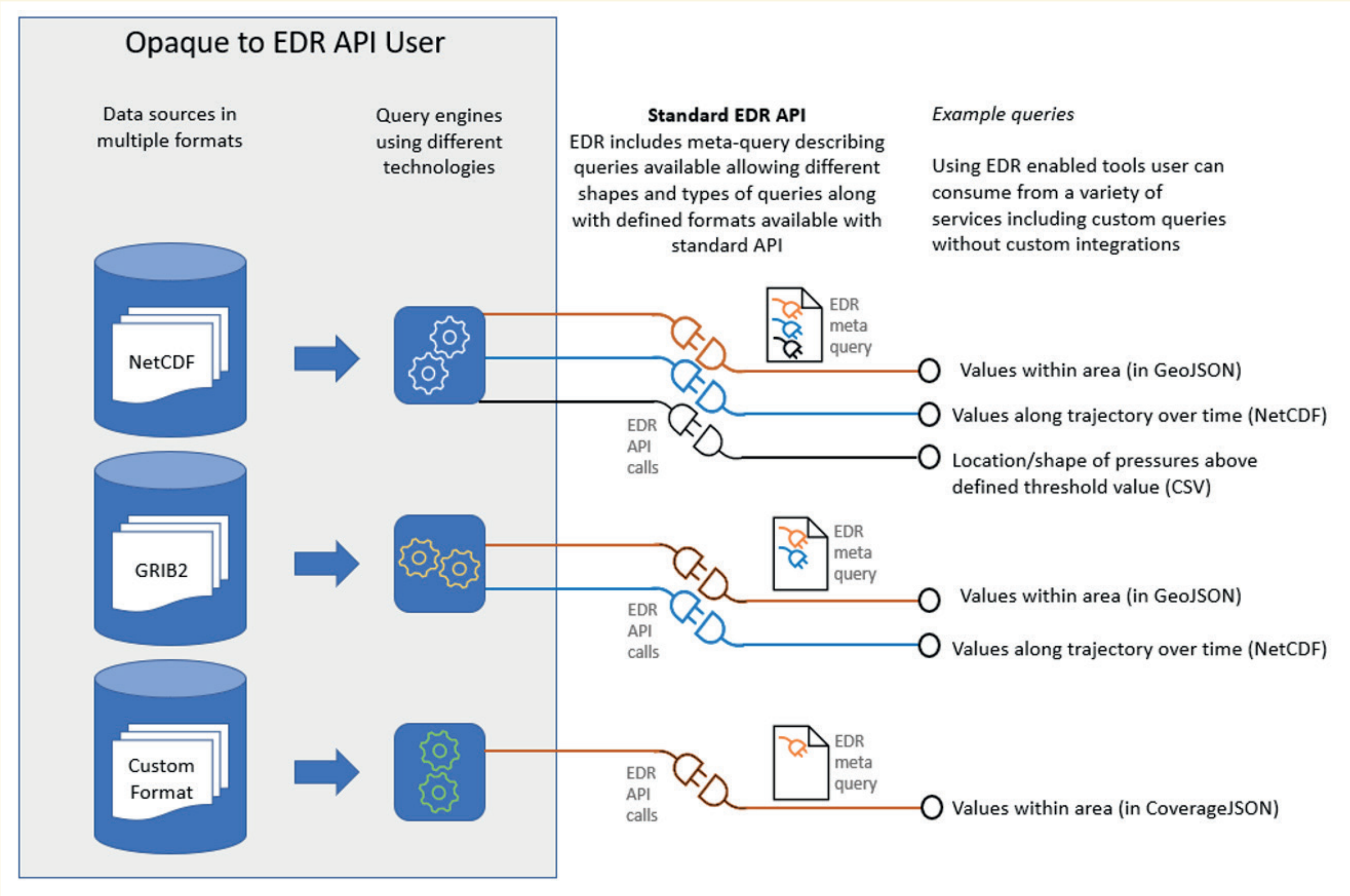
Decoupling the data storage and standardising the approach to top level metadata would help reduce these issues. A consistent and domain agnostic approach to describing the available data makes it easier for data consumers to identify suitable data and a query interface that can be migrated to new data sources reduces the need to update client applications.

Rather than creating a bespoke solution, the Met Office presented a web services prototype to an Open Geospatial Consortium (OGC) technical conference, an organisation responsible for setting international geospatial data standards. Engaging with other OGC Members comprising of individuals from vendors, users and government entities the concept demonstrator evolved into the OGC API - Environmental Data Retrieval (EDR) API.

The EDR standard uses web technologies and best practice to enable non-experts to easily identify and retrieve a subset of environmental data from data stores. It can be considered a ‘Sampling API’, the important aspect is that the data required is specified by spatio-temporal coordinates and a list of the required parameters which is a level of abstraction that supports querying a large range of static and dynamic data sources.

To reduce the overhead on data publishers the Environmental Data Retrieval (EDR) API is based family of lightweight interfaces, the data publisher only needs to implement those interfaces that are appropriate for their data.

The specification consists of two types of operation: discovery and query. Discovery operations allow the API to be interrogated to determine its capabilities and retrieve information (metadata) which describes which EDR query operations are supported, the spatio-temporal extent of the data and the data parameters that are available. Query operations allow data to be retrieved based on simple selection criteria and the range bounds for the selection criteria are defined in the discovery operation response.



C. Pioneering Research

C.1 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 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 work with the Advancing Observations theme to supplement our high quality core observing networks with data from other sources 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

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 goal 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 work with the Advancing Observations theme to 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 initialization (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.

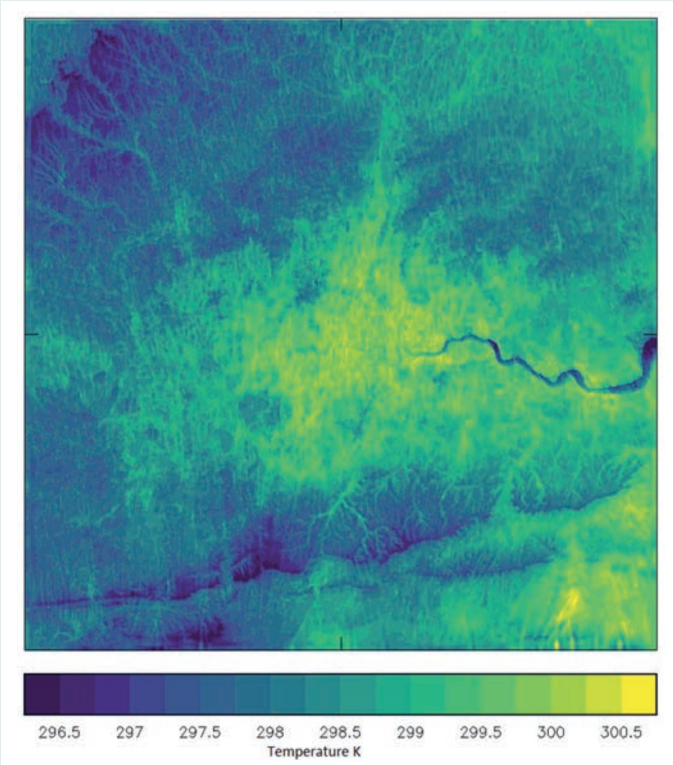


Figure 16 - Instantaneous screen level temperature (degrees Kelvin) in a 100m simulation over London. The detailed signature of small-scale features in the land surface (e.g. valleys and the River Thames) are visible.

C.2 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.

To maximise the value of ensemble prediction it is important that forecast systems are well designed to maximise skill while optimising spread, maintaining reliability and ensuring that ensemble members are realistic analogues of observed weather and climate. 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 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 to make the most skilful predictions across timescales, while developing new and novel uses of ensemble information for improved understanding of weather and climate.

To achieve this goal 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 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 and hazards.
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 its own ensemble members. 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.

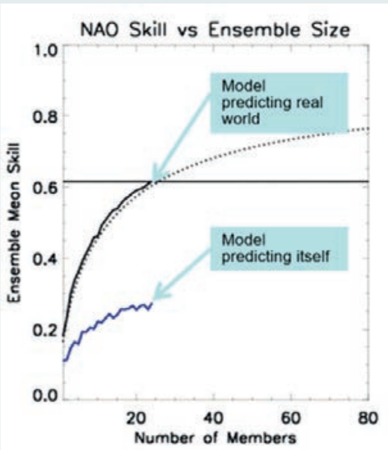


Figure 17 - Increasing skill of winter seasonal predictions with ensemble size. The black solid curve shows correlation scores of forecasts for Dec-Jan-Feb mean North Atlantic Oscillation as a function of ensemble size of up to 24 members. The blue line shows the same quantity for the model ensemble 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 in 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 in the tropics, enhancing forecasts and warnings in support of our international partners and civil protection agencies.

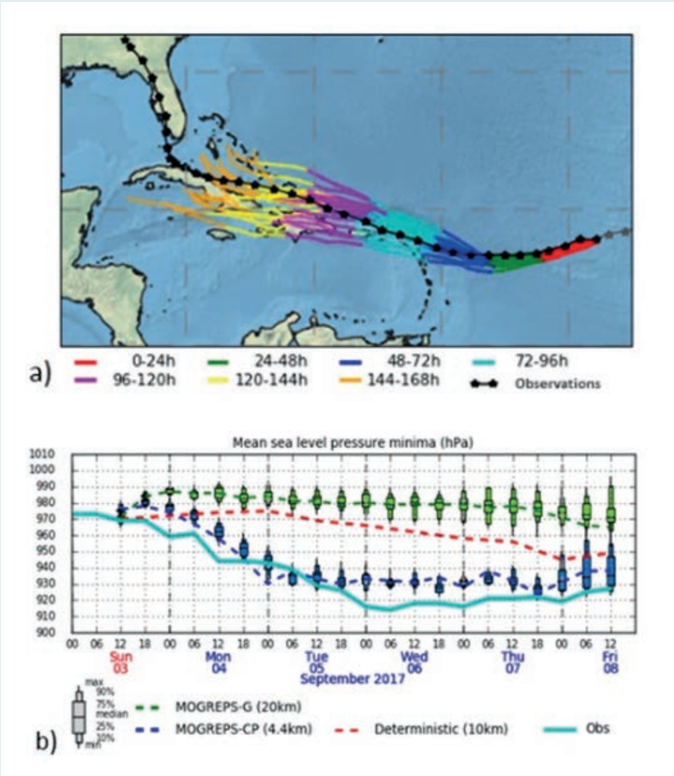


Figure 18 - Forecasts for Hurricane Irma (September 2017) from the MOGREPS-G global ensemble (20km resolution) and the equivalent prototype MOGREPS-CP convection permitting 4.4km ensemble: a) 7-day track forecast from MOGREPS-G; b) 5-day intensity forecasts (minimum sea-level pressure) from both MOGREPS-G and MOGREPS-CP, illustrating how the 4.4km model provides a much better forecast for the rapid intensification on 4th September.

C.3 Capturing Environmental Complexity

Alongside increases in resolution and advances in ensemble prediction, including relevant environmental complexity in our seamless simulations will be crucial to meet demands for improvements in forecasting ability and climate prediction across all time and spatial scales and to support the simulation of weather and climate impacts. The Earth's climate and weather systems are heavily influenced by factors and processes such as the carbon cycle, vegetation, wildfires and 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.

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 (for example accelerated sea level rise due to collapse of Antarctic ice sheets). An increased understanding of the Earth System is vital for developing 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.

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
- Model hierarchy approaches including for events with low likelihood but high potential impact

Goal

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

To achieve this goal 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; monitoring and detecting long-term changes through attribution approaches and inversion modelling; and developing early warning of high impact, low likelihood climate outcomes such as crossing climate tipping points.
4. Probe the workings of the Earth system using our world-class modelling systems as a computational laboratory, including contributing to and using digital twin approaches.
5. More clearly understand and communicate the benefits and costs of adding extra environmental complexity to models, contributing to the debate on how to balance resourcing decisions involving changes in resolution, ensemble size and model complexity.

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: i) options for meeting carbon budgets (such as biofuel, tree-planting, carbon capture), ii) the climate and emissions pathways compatible with a range of climate targets and iii) 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.

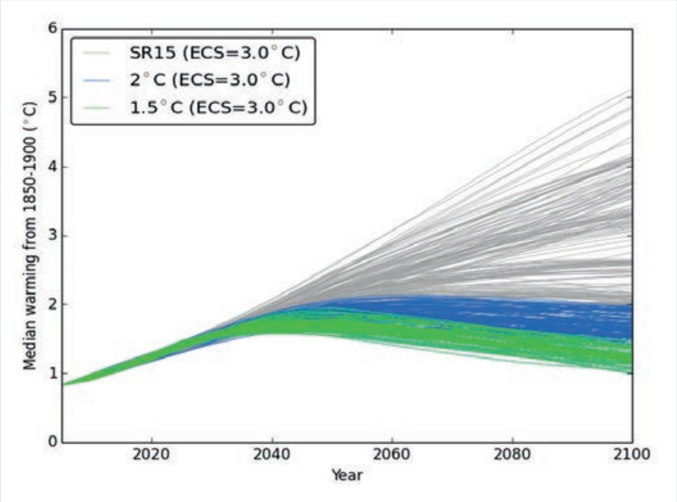


Figure 19 - Median warming estimated for the scenarios used in the IPCC 1.5°C special report, reprocessed with an equilibrium climate sensitivity of 3°C. The grey pathways exceed 2°C in 2100. The blue pathways limit 2100 warming to below 2°C. This would require mitigation pathways characterized by energy-demand 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.. This includes reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers, particularly methane

Our most recent work has focused on using a simple climate model that is traceable to the IPCC 6th assessment report. We have examined the climate response to emission pathways that are compatible with the 2030 greenhouse emissions corresponding to the emission pledges considered during CoP26 to understand what action is needed to meet the Paris agreement targets.

Developing new Flagship projects

In this theme we are currently developing new flagship projects on interactions between climate change and air quality, and high impact low likelihood events. For instance, we will work with the NERC multi-centre project TerraFirma to downscale high-resolution time slice simulations of UKESM, achieving a resolution of ~ 2km over the UK with the Regional Environmental Prediction model. These simulations will allow us to investigate interactions between future climate change and air quality, including assumptions around future pollutant emissions over the UK. Simulations will include key air quality indicators (PM2.5, NOx, surface ozone), climate drivers of air pollution (heatwaves, stable boundary layers etc) and consideration of their link to local emissions and remote advected pollutants. This is an important and ambitious project because air pollution is a major risk to human health, with global excess mortality estimated at 8.8 million/year. In addition, there is increasing interest in considering co-benefits and trade-offs of different mitigation strategies, aiming to maximise their benefits for both climate change and air quality.

D. Cross-cutting Themes

D.1 People

As referenced in the People Strategy, 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.

Goals

By 2030 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 new pilot roles. 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.

Figure 20 - Mairead Cooke will begin one of the brand new pilot roles in 2021.

D.2 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, technology and innovation needed to serve the full breadth of our societal need for services, while developing and maintaining the critical operational services.

Goals

By 2030 we will focus on the following areas aiming to:

1. Develop our new supercomputing partnership with Microsoft to deliver effective and innovative, high performance, high availability and cost-effective large scale heterogeneous supercomputing data storage, and data science platforms.
2. Develop and nurture our other 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 goals and mutual benefit.
3. Build new partnerships to specifically support delivery of the Research and Innovation themes, including leveraging our new Microsoft partnership to open, develop and promote new collaboration and innovation opportunities
4. 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.
5. 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

Microsoft Supercomputing Services

The Met Office has partnered with Microsoft for the next 10 years (2022 to 2032) to provide two technology generations of supercomputing capabilities, delivered through a full managed service commercial model. This new partnership will provide best in class supercomputing technologies, performance, and scale which will ultimately provide more than eighteen-times (18) more compute capacity to the Met Office's weather and climate science research and innovation strategy, teams, and partners. The new capabilities will open a unique opportunity to innovate massive scale supercomputing services which are interconnected directly into a global Cloud platform provider and innovator.

The Met Office intends to carefully deepen its new partnership with Microsoft in the areas of heterogeneous supercomputing platforms, massive scale data storage/archive technologies, machine learning compute services, disruptive AI principles and large-scale compute-as-a-service operating models. In addition, the Met Office aspires to leverage Microsoft's partner ecosystem to develop opportunities for accelerating change delivery pace and technology innovation adoption, working closely with class leading technology pioneers such as HPE/Cray and AMD.

The Met Office's overriding aim is to create, encourage and promote opportunities for collaboration in the areas of environmental data science and services as well as drive increasingly cost-effective reach, all within the arena of consumption-based supercomputing-as-a-service.

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 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.

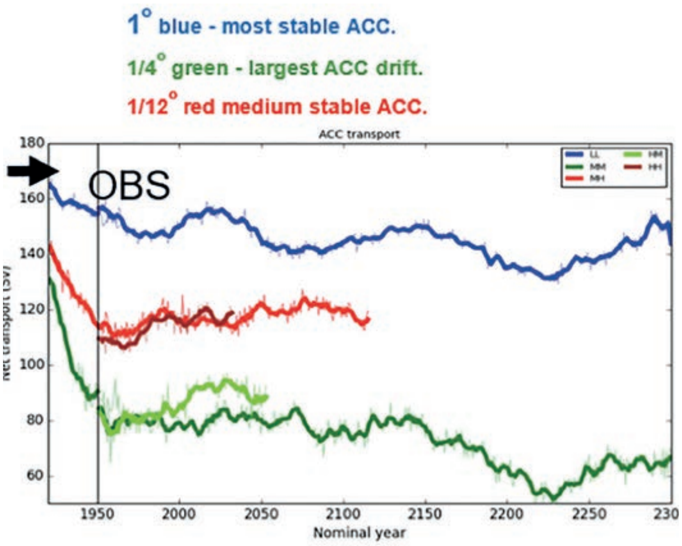


Figure 21 - The eastward volume transport (Sv) through Drake Passage, the strait between South America and the Antarctic Peninsula, for a set of models with different ocean and atmospheric resolutions. The blue, red and green lines represent models at ocean model resolutions of 1° (~100 km), 1/4° (~25 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.

DEEPMIND PANGEO The Environmental Futures & Big Data impact lab

Figure 22 - A synthetic radar image from the nowcasting project with Google DeepMind.

D.3 Practices

Our investment in next generation supercomputing, NGMS and the associated exploitation programmes provide the opportunity to continue to evolve our practices that enable us remaining at the cutting edge. In doing so we will challenge ourselves to achieve higher standards in key areas such as security, data management, process and asset management maturity.

We will increasingly distinguish the national capability from our services portfolio and apply appropriate practices in each to balance the needs of research and innovation whilst protecting operational delivery.

Goals

By 2030 we will focus on the following areas aiming to:

1. Deliver clearly defined and well managed boundaries between the National Capability and our portfolio of services enabling us to increase the rate of science and technology innovation and at the same time protect our customer services.
2. Achieve high standards of security and operational excellence in building the new world to balance the need of research and innovation against operational workloads across common, shared platforms.
3. Be recognised as being a model of good practice in how we approach our science and software engineering disciplines.
4. Be clear and consistent in understanding our service commitments to customers, stakeholders and collaborators irrespective of whether we are operating in research, innovation or operational modes.
5. Embed understanding of the importance of identifying, capturing, and managing knowledge assets and Intellectual Property (IP) that support the science and technology innovation to actively promote the protection of assets, bring clarity of those assets with potential for exploitation and to reward and recognise contribution where knowledge assets and IP deliver benefits and have impact.

To achieve these goals, we will:

- Unify practices across Science and Technology to simplify working together, delivering more effective outcomes from the National Capability and breaking down internal siloes of working.
- Continue to embrace and adopt contemporary working practices from across industry and research organisations that support our ability to innovate whilst maintaining operational excellence.
- Rely on process maturity and workload management tools to separate research and innovation from operations in favour of platform separation.
- Extend our partnerships approach from the world of research into the world of operational delivery, ensuring we can scale to meet the challenges of the next 10 yearsDevelop clear, simple standards that define the service levels we will offer from the national capability and our responsibilities in committing to these.
- Develop Knowledge Assets and IP management capabilities with clear accountabilities and responsibilities for considering the protection and exploitation of our knowledge assets and IP.
- Establish a culture and working environment in which we reward and recognise Knowledge Asset and IP protection and exploitation.

Case study

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.