



Australian Government
Bureau of Meteorology

Research and Development Plan

2020–2030

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FOREWORD



The Bureau of Meteorology is constantly striving to advance prediction services in order to improve public safety and save lives, increase quality of life, protect infrastructure and the environment, safeguard economic sectors and increase socioeconomic benefits.

Over recent decades, weather, climate and environmental prediction has become increasingly complex and more accurate across all time and space scales. As such, we are seeing a corresponding growth in the application of forecasts and subsequently an increasing demand for forecasters to add value through communication of forecast-based decision-making information and liaison with the community and our customers.

In response, this Research and Development Plan 2020–2030 sets the direction for the Bureau's investment in research and development over the next decade through description of four overarching objectives. Underpinning our products and services, focussed research and development is critical to enable us to deliver better information and insights to our customers.

Today, our customers act on reliable forecast information to plan their activities weeks ahead, something that was impossible just two decades ago. While great strides have been made in enabling our customers to utilise our predictions of future weather, there remains significant demand for further improvements, such as greater accuracy, higher resolution, more frequent updates and descriptions of uncertainty they can act on. This applies across weather, climate, oceans, hydrology and the land surface, from the coming minutes and hours, through to decisions made over weeks, months and even decades ahead.

With appropriate investment in our science and technology, we will deliver to these demands, and in the future our customers could be acting on real-time situational data at the street level, with forecasts updated every five to ten minutes on hazards such as the likelihood of hail, damaging winds, flash flooding locations and hazardous driving conditions. Such improvements would provide significant value to the nation and our communities.

With focus on delivering the four objectives articulated in this plan, we will strive to be an organisation where our world-class scientific and technical capability underpins and fundamentally transforms our processes, products and services, making a profound difference to our customers and stakeholders, and creating shared value with our partners. Achieving this will depend on the collaboration, strength, commitment and excellence from across the entire Bureau.

A handwritten signature in black ink, consisting of a large, stylized 'G' followed by a series of loops and a final vertical stroke.

Dr Gilbert Brunet

Chief Scientist and Group Executive, Science and Innovation



1. EXECUTIVE SUMMARY

The Bureau is focussed on delivering world class services for all Australians – in line with goals of contributing towards zero lives lost due to meteorological and oceanographic hazards and the provision of billions of dollars of additional economic value to the nation.

More accurate and reliable forecasts will be crucial to enable mitigation of hazards to save lives and create financial benefit for industries such as energy, transport, aviation, water and agriculture through avoided losses and enhanced opportunities for revenue. With the right insights and decisions, our communities, economy and sectors can prosper.

Through delivery of four inter-dependent research and development objectives, we will provide enhanced value and impact to our customers, leading to significant socio-economic benefits over the next decade. This will be driven by focus on targeted improvements to both our underpinning numerical prediction capabilities and to our forecast delivery and services based on customer needs, to deliver more accurate, timely, and tailored insights over the next decade.

OBJECTIVE 1: We will develop higher-resolution, more localised, customised and accurate forecasts, updated hourly for cities and regional areas, specifically delivering to the needs of our customers. This will be combined with nowcasting tools optimised to provide customers with enhanced decision support and more timely forecast updates prior to and during high impact weather.

OBJECTIVE 2: We will enhance the quality of, and increase, when and where appropriate, the quantity of observational data for analyses and for assimilation into our models, to provide more precise, accurate and reliable information.

OBJECTIVE 3: We will develop a full Earth system numerical prediction capability with coupled subcomponents, to deliver a wider breadth of information-rich data that is consistent across the atmosphere, land, ocean, waves, sea-ice and hydrology. This Numerical Environmental and Weather-climate Prediction (NEWP) system will be aligned to the World Meteorological Organization (WMO) Earth system framework and approach, and enable prediction of multi-hazard events in a fully consistent manner.

OBJECTIVE 4: We will develop seamless weather and climate risk-based services, providing insights from minutes to decades to enable improved decision-making and risk reduction. This will include the integration of historical observations, forecasts with a full characterisation of uncertainty from minutes to seasons, and projections for the coming decades.

These objectives will be underpinned by significant advances in computing and data capabilities, collaboration with our partners both nationally and internationally, and a focus on developing the skills and expertise we need for the future.

2. STRATEGIC CONTEXT

2.1 KEY DRIVERS

The Bureau is operating in a rapidly evolving world, with global trends shaping the demands of our customers and the way we work and operate.

Risk-based decision-making is becoming more important with population growth, particularly in our major cities. More people and assets are exposed and vulnerable to weather, climate, water and ocean hazards. The essential services we rely on – power, water, telecommunications, the internet and finance – are also exposed to these hazards. Our customers are increasingly demanding more localised and accurate information, frequent updates and tailored services for better decision-making needs over multiple time scales.

High-performance computing (HPC) infrastructure is rapidly changing. Migration of numerical prediction systems to new and evolving HPC infrastructure is an ongoing challenge requiring significant effort.

Data volume and complexity is rapidly increasing as greater amounts of satellite, radar and third-party data become available, the size of our model output grows, and the frequency of model runs increases.

Transformative approaches to data science, such as artificial intelligence and machine learning also continue to rapidly evolve, influencing the way we work.

Antarctica, the Southern Ocean and the Pacific continue to be strategic priority areas. We will invest to better understand the dominant processes in these regions and enhance our modelling capabilities for improved services for our customers and partners.

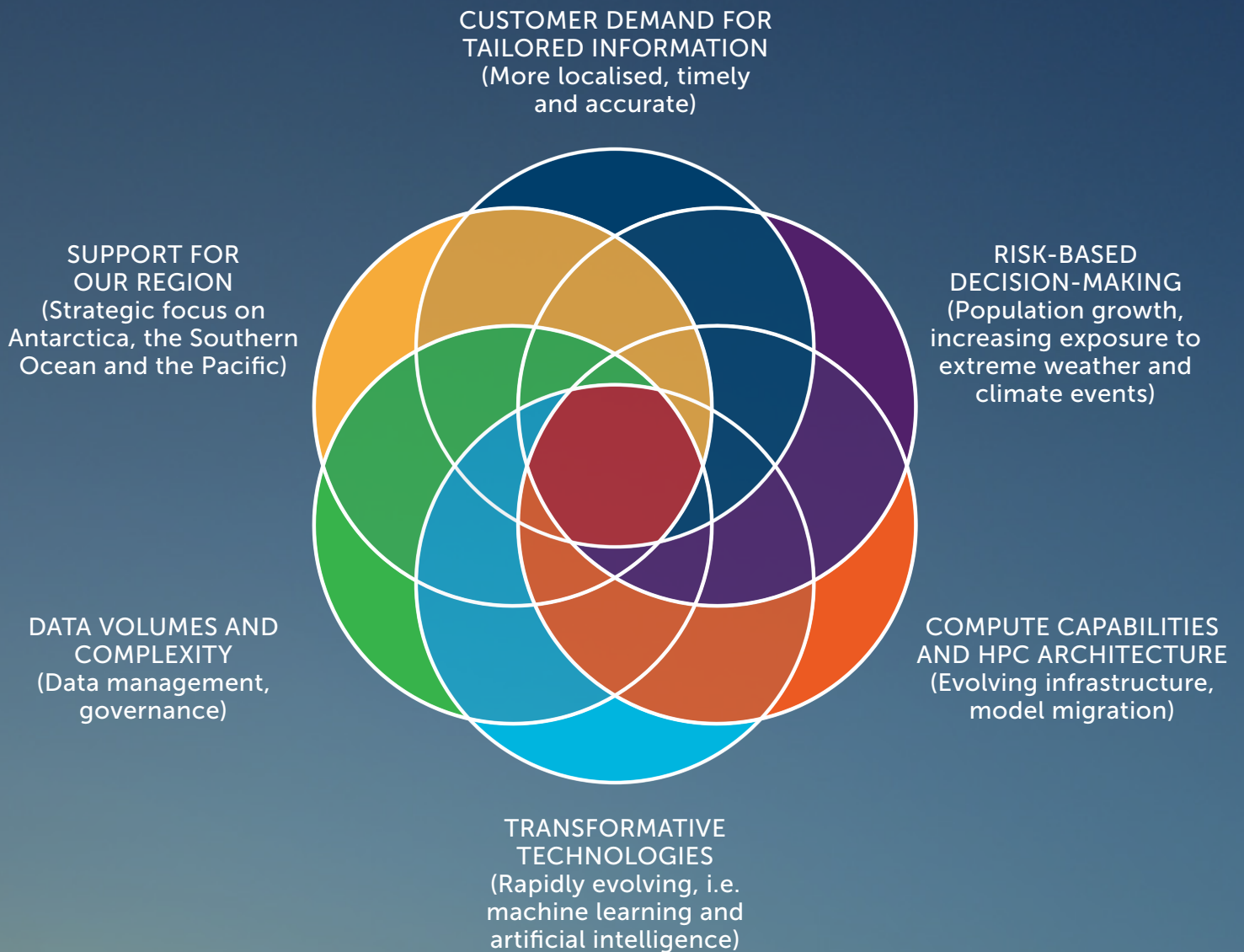


Figure 1: Key drivers influencing the Bureau's research and development efforts over the next decade.

2.2 DELIVERING THE BUREAU'S STRATEGY

The Bureau is focused on delivering world class services for all Australians – in line with goals of contributing towards zero lives lost due to meteorological and oceanographic hazards and the provision of billions of dollars of additional economic value to the nation.

Delivering these benefits requires focussed effort in research and development and is predicated on improvements in the accuracy of Earth system model predictions, as seen over the last half century. Investment in observations, data, models and computing power are critical to achieve these goals, but are insufficient without the scientific insight and knowledge to enable these tools to be brought to bear on the challenge of providing more skilful, nuanced and reliable information, further into the future, on more localised scales, and of most relevance to our customers.

The Bureau's Strategy is centred on an improved customer experience, the core of what we do and what drives our investment in science and technology. With targeted investment in both public services, and in partnerships with industry and private enterprise, all Australians will benefit from our science and technology improvements. These investments will enable us to achieve the Bureau's strategic mission.



Figure 2: The Bureau's Strategy is centred on an improved customer experience and the delivery of national benefits.

**The Bureau's mission is to
'provide trusted, reliable
and responsive weather,
water, climate and ocean
services – all day, every day'.**



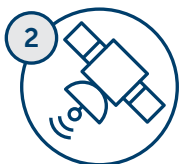
3. RESEARCH AND DEVELOPMENT OBJECTIVES

We will focus our research and development efforts over the next decade on the delivery of four inter-dependent research and development objectives. The four objectives operate as a 'system of systems', each contributing to enable improvements in model accuracy and downstream products to deliver more accurate, timely, and tailored insight to our customers over the next decade.



OBJECTIVE 1: CUSTOMISED IMPACT-BASED FORECASTS AND WARNINGS WHEN AND WHERE IT COUNTS

More localised, timely and better information for cities and regional areas



OBJECTIVE 2: RELIABLE AND TRUSTED FORECASTS

Enhanced assimilation of observations for more accurate predictions



OBJECTIVE 3: AN EARTH SYSTEM NUMERICAL PREDICTION CAPABILITY

Fully integrated atmosphere, ocean, sea-ice and hydrology models



OBJECTIVE 4: SEAMLESS WEATHER AND CLIMATE INSIGHTS

Historical observations and predictions, from minutes to decades

Each objective relies on the parallel advancement of each of the other objectives. For example, delivery of more localised and timely information (objective 1) is reliant on enhanced observations and data assimilation (objective 2), along with advances achieved through development of a full Earth system capability (objective 3). Likewise seamless weather and climate insights (objective 4) will enable identification of numerical prediction biases to improve short-term forecasts (objectives 1 and 3). Achieving these objectives is also reliant on the adequate availability of HPC resources and its optimal utilisation.

Inter-dependencies of the four research and development objectives

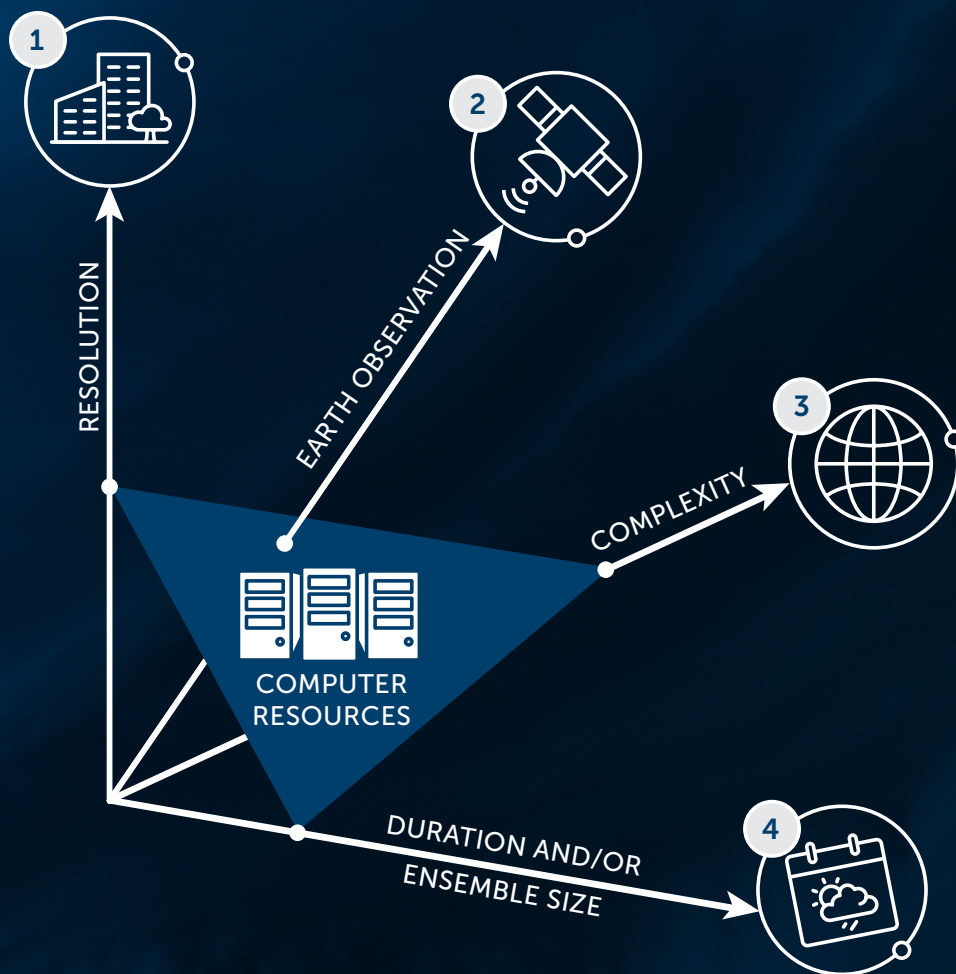


Figure 3: The four objectives operate as a 'system of systems', each contributing to enable improvements in numerical prediction accuracy and downstream products to deliver more accurate, timely, and tailored insight to our customers over the next decade. Each objective relies on the parallel advancement of each of the other objectives, and as such, effort towards any objective in isolation will hinder the ability for success. Achieving these objectives is also reliant on the adequate availability of HPC resources and its optimal utilisation.



OBJECTIVE 1: CUSTOMISED IMPACT-BASED FORECASTS AND WARNINGS WHEN AND WHERE IT COUNTS: MORE LOCALISED, TIMELY AND BETTER INFORMATION FOR CITIES AND REGIONAL AREAS

For cities and urban areas, there is growing demand for high-impact weather forecasts. Likewise, regional demand will grow for many environmental prediction systems at the sub-kilometre scale in complex terrain. Sub-kilometre models from the Australian Community Climate and Earth System Simulator (ACCESS) are already demonstrated for high-impact weather events, and will increasingly be operational in Australian capital cities. Better water management in urban areas is increasingly important as water shortages occur more frequently and flooding affects more people due to higher population densities in areas at risk, such as along the coast and within river catchments.

Kilometre and sub-kilometre scale resolution models will include a realistic representation of the effects of large cities to ensure reliable prediction of the water cycle, energy budget, atmospheric flows and dispersion in complex urbanised environments. Peri-urban and rural regions will also benefit from increased resolution models where fire is a major hazard. Improvements to numerical weather modelling will also include greater physical realism from improved physics and spatial resolution, assimilation of a larger number and variety of observations, more frequent (hourly) updates, and ensemble approaches to represent uncertainty.

High-impact nowcasts of weather for the next few hours will be based on optimal blends of remotely sensed and in situ observations, NEWP inputs, and data from third party networks. New science on incorporating non-traditional data types such as public reporting of events in social media into nowcasts will enable richer situational awareness internally and externally to the Bureau and contribute information that can be used to verify forecasts of hazard impacts.

Nowcast and NEWP systems will routinely be statistically post-processed to further improve accuracy, specificity, and statistical reliability. Probability distributions of all major variables of interest will be produced, allowing routine and on-the-fly generation of probabilistic forecasts for exceeding fixed and user-specified thresholds and tailoring of risk-based decision support to meet specific customer needs. Post-processing will also generate diagnostic variables such as severe thunderstorm indicators that will enable our meteorologists to better understand and communicate hazardous weather to our stakeholders.

There will be increased coupling of nowcasts and NEWP with downstream models to predict flooding and streamflow, fire behaviour, air quality, marine conditions, solar and wind energy, airport conditions, and many other applications. These will extend further down the value chain to impact-based forecasts of damage to, for example, infrastructure, human health and economic costs. This information supports the Bureau to better predict hazards and their impacts with increased focus on customer needs. It will also feed direct (i.e. machine-to-machine) decision support systems operated by our stakeholders. Integrated science-based decision support will be co-designed and co-developed in partnership with users of this information to enable them to best plan for, and respond to, high-impact events. For cities, effective response can be especially complex, and weather and environmental modelling at the urban scale will assist in risk assessment and response planning.

The multi-cultural and diverse nature of the population creates challenges for effective warning communication. At the same time, people and

industries want the most up-to-date weather and environmental information to support their decisions. Social science will be an increasingly

important activity for the Bureau and our research partners to ensure that warning messages are effectively conveyed.

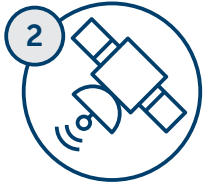
3-YEAR TARGET	5-YEAR GOAL	10-YEAR VISION
Impact forecast and warning services, improved decision support and automation, national high spatial resolution analysis system and a national high-resolution, ensemble-based water prediction capability	Best-practice localised impact forecast and warnings services designed using social sciences and underpinned by very fine spatial resolution and rapidly updating urban and regional models	Fully integrated and continuously updated multihazard and impact-based probabilistic analysis, forecast, and warnings for urban and regional applications
DELIVERED THROUGH:		
<ul style="list-style-type: none"> • A future warnings framework road map; • Australian Safety and Alerting Program issuing alerts based on customer driven parameters and the triggering of warnings for heatwave, flood, fire and tropical cyclone; • Quantitative performance measures of inputs and outputs including socio-economic impact assessment in at least twenty-five per cent of post-event reviews; • Automation of most routine condition weather forecasting; • Implementation of calibrated fully probabilistic weather, monthly and seasonal guidance; • Introduction of ensemble, short-term and seasonal national water and streamflow forecasts with assimilation and post-processing to meet customer needs; • More frequent high-resolution prediction, with ensembles (ACCESS-C/CE3) and rapid update analyses (Mesoscale National Analysis System); • Enhanced tropical cyclone prediction with high resolution modelling (ACCESS-TC3) and extended bias correction of global prediction systems. 	<ul style="list-style-type: none"> • Evaluation and re-refresh of the future warnings roadmap to continue process of transition of science to services; • Enhanced warning services for priority hazards and insight into the impact of hazards on at-risk communities and industries; • User relevant performance metrics; • Automated weather forecast production near one hundred per cent in routine conditions and for some services in non-routine conditions; • Production of calibrated probabilistic basic weather and initial multi-hazard and impact guidance, including rapid updates and nowcasts, and incorporating use of machine learning; • Integrated meteorological and hydrological systems for urban and regional domains; • Benchmarking of one hundred to three hundred metre model capabilities for priority Australian domains and as part of Paris Olympics Research Demonstration Project. 	<ul style="list-style-type: none"> • Fully probabilistic datasets; • Regional environmental threats and impacts updated every ten minutes for the next few hours and at least hourly for multi-day forecasts; • Near-complete weather forecast automation; • Sub-kilometre scale regional datasets; • Urban scale (less than one kilometre resolution) models, including coupled fire modelling; • Improved urban and marine coupled boundary layer simulations for more accurate nocturnal boundary layers, tropical cyclone tracks and intensity, frosts, squall lines, water quality, groundwater, fog and ocean upwelling.



Benefits

- Reduced injuries and fatalities from severe weather events and hazards through better informed decisions by individuals and communities;
- More effective operations by customers such as the emergency management, water, energy, resources, agriculture, transport, and aviation sectors with provision of more accurate, timely and probabilistic nowcasts and forecasts in urban and regional locations;
- Improved decision-making by customers through an enhanced ability to extract decision-enabling information from large model and observational datasets;
- Improved accuracy of numerical prediction products enabling improved decision-making;
- Improved accuracy and greater confidence in numerical products resulting from enhanced verification and monitoring;
- Improvements to warnings and automated data delivery through timely and accurate nowcast and model-based datasets.

	BY 2022	BY 2025	BY 2030
KPI 1.1:	Five-fold increase in forecast 'delivery rate' (=resolution x update frequency).	Ten-fold increase in forecast 'delivery rate'.	Twenty-fold increase in forecast 'delivery rate'.
KPI 1.2:	Ninety per cent automation levels for baseline forecast services, while maintaining or improving service levels.	One hundred per cent automation levels for baseline forecast services, while maintaining or improving service levels.	One hundred per cent automation levels for baseline warning services, while maintaining or improving service levels.
KPI 1.3:	Seventy-five per cent of customers satisfied with customised forecast and warnings products, measured through annual survey.	Eighty per cent of customers satisfied with customised forecast and warnings products, measured through annual survey.	Ninety per cent of customers satisfied with customised forecast and warnings products, measured through annual survey.
KPI 1.4:	Five per cent year-on-year increase, over initial benchmark, in number of customers using customised forecast and warnings products, based on internet downloads/views.		



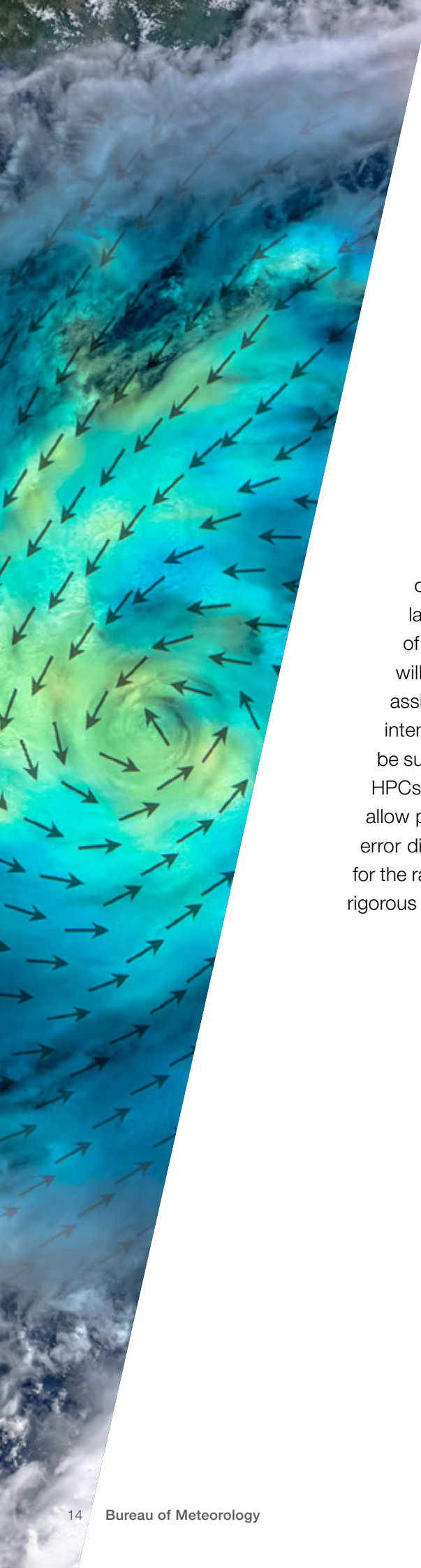
OBJECTIVE 2: RELIABLE AND TRUSTED FORECASTS: ENHANCED ASSIMILATION OF OBSERVATIONS FOR MORE ACCURATE PREDICTIONS

Data assimilation and observations research seeks to enhance the accuracy and reliability of forecasts by improving the starting conditions for forecasts. This means increasing the current and future observational capability and ensuring its optimal use in forecasting high-impact weather. For example, this research supports designing regional observing networks, and developing well-founded strategies for enhancing observations. Over the next decade, we will see better integration of observing systems in order to support optimal global and regional NWP systems. An integrated observing network will meet the demands of weather and climate forecasting spanning time scales of minutes to decades in a cost-effective manner. This will include climate monitoring with NWP-generated analyses that meet the exacting requirements of climate science: not only accurate quantities, but, for example, accurate fluxes as well.

The Bureau assimilates a wide range of observations, from satellite measurements to in-situ observations. Modern global NWP systems have horizontal resolutions in the order of ten kilometres and use simplified parameterisations for unresolved processes. In the next decade, we will see global models approaching one kilometre resolution and regional models at subkilometre resolutions. These models give much improved forecasts of high-impact weather by explicitly representing the nonlinear and turbulent processes of clouds and storms. Innovative and efficient data assimilation systems will need to account for these characteristics properly, including different modelling and observational scales, and in the context of evolving global and regional observation networks.

The Bureau will continue to use land and ocean-based in-situ surface observations and upper air profiles of water vapour, pressure temperatures and clouds obtained collectively from sondes, profilers, and aircraft observations. In the future we should see a significant increase in these observations, with an expanded role for drones, and improved international dissemination of the data to all NWP centres. New variables, such as greenhouse gas concentrations, will be measured by aircraft including commercial carriers. The Bureau will make use of new sources of data, especially for convective-scale models, such as Light Detection and Ranging (LIDAR), crowd-sourcing sites and mobile phone technology. In addition to the regular observing network, cost-effective adaptive observations will be obtained for high-impact weather events, as has already been demonstrated for tropical cyclones. However, these should not be a replacement for the conventional observations, which anchor the observing network, but rather as a means of improving coverage in the future.

The Southern Hemisphere, including Australia, currently has good satellite-based coverage of surface and atmospheric observations. This will increase dramatically in the future with more observations of land, cloud and sea-ice. Currently, data is thinned to reduce error correlations between measurements. In the future this will be overcome by directly accounting for these correlations. This will permit substantially greater volumes of data to be assimilated compared with the current twenty per cent usage level. Data from active space-based microwave radars will be routinely assimilated, providing valuable information for the prediction of precipitation and moist processes.



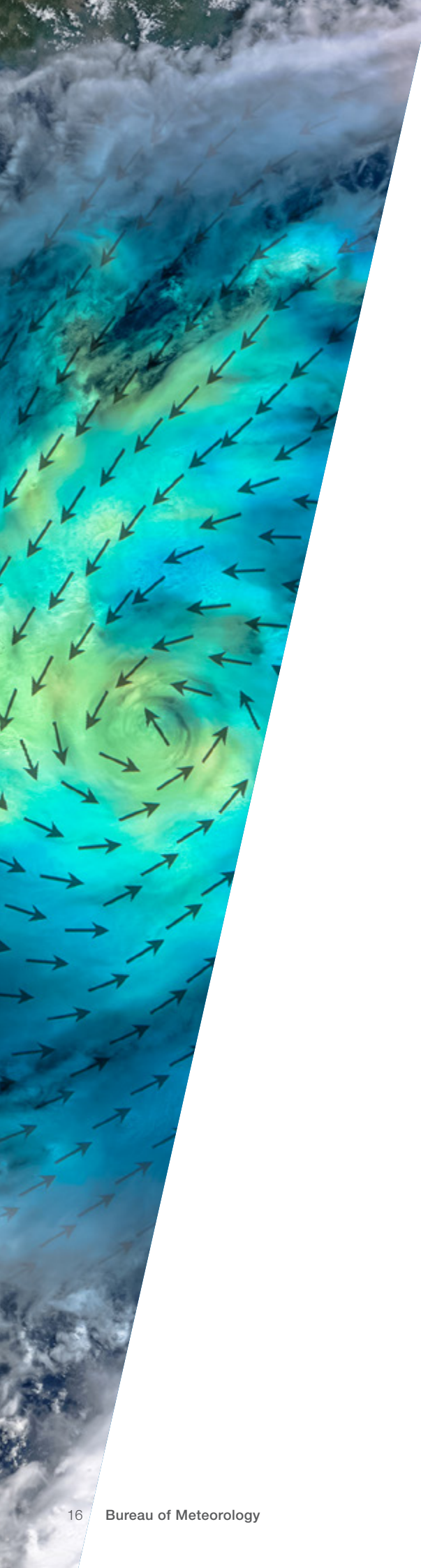
In-situ observations of the ocean (pressure, wind and sea-surface temperature) come mainly from the drifting buoy network introduced in the late 1990s, supplemented by moored buoys and ships. There are many more existing ocean platforms providing data which are not currently assimilated, that will be required with the move to coupled NEWP. We should see an increase in the use of autonomous platforms like floats to provide profiles of temperature and salinity to ocean depths beyond the two thousand metre limit of Argo floats. It is noteworthy that satellite ocean-colour observations will be routinely assimilated and predicted for use in estimating chlorophyll concentration and phytoplankton characteristics.

Data assimilation will be the cornerstone of NEWP which will bridge models and atmosphere–ocean–land–cryosphere–biosphere observations. Data assimilation algorithms that can accommodate large numbers of observations will remain the preferred building blocks of most NEWP operational systems in the short-term, but these systems will be replaced increasingly by hybrid ensemble and variational data assimilation schemes, as is already occurring. While still computationally intensive, especially for increasing ensemble sizes, these algorithms will be suitable for implementation on the next generation of massively parallel HPCs. As horizontal resolution increases, these assimilation techniques will allow practitioners to focus more on observation types with more complex error distributions, such as cloud and precipitation. Methods that account for the random fluctuations in variables across a grid cell will also have a more rigorous bias.

3-YEAR TARGET	5-YEAR GOAL	10-YEAR VISION
Fully utilise existing observing technologies and targeted deployment of new instruments	Significantly increase the volume of fit for purpose observations assimilated, consolidate national water quality data and build capability for non-traditional observations	Substantial increases in data assimilated, and much greater variety of traditional and nontraditional data sources used in our systems

DELIVERED THROUGH:

- Advanced observational capabilities integrated with operational systems for improved situational awareness and nowcasting of severe weather (rainfall, hail, wind, lightning) from improved radar capabilities, blending of radar, satellite, and NEWP, and the development of a high-resolution rapid update analysis;
- Greater availability of satellite-derived inputs for numerical weather and water prediction (for example, GPS observations);
- Extended verification capabilities due to additional observations;
- Coupled ensemble data assimilation for multi-week to seasonal prediction in both numerical weather prediction and water models;
- Point data assimilation into landscape models;
- New deployments of advanced ground-based instruments observing clouds and the boundary layer in the Antarctic, Southern Ocean, Indian Ocean and Tropics;
- Robust tools to quantify the value and quality, including uncertainty characteristics, of observed data to numerical prediction systems and automated operational forecast processes, with feedback into observing network design and management.
- More than ninety per cent of satellite observations available for assimilation, and land surface observations for hydrological modeling, as benchmarked against leading global centres;
- National water quality data platform created;
- Participate in national and international field programs;
- Frameworks to assess and efficiently integrate new third-party variable quality observations and networks;
- Establishing partnerships with social media providers;
- Timelier, localised, accurate and seamless short-range predictions blending observations and numerical weather prediction;
- Use of third-party observation data within modelling systems.
- Volume of data integrated into forecast systems is on par with leading international peers;
- Products and models utilising observations from new sources like mobile devices (phones, cars), micro satellites, crowd sourced, closed circuit television (CCTV) cameras and social media;
- Use of unconventional observation data within modelling systems;
- Improved ability to extract decision-enabling information from our large model and observational datasets through machine learning, data science and big data analytics.



Benefits

- Increased number and quality of observations (particularly radar, satellite and GPS) available to enhance nowcasting, rapid update forecasting, sub-seasonal through to seasonal forecasting;
- More observations available for forecast guidance, verification, model improvement and evaluation as well as post-processing to user needs, for specific high-value applications (for example, urban and regional domains);
- Measured benefit of our observing networks on numerical prediction systems and products;
- Better understanding of fundamental processes informed by observations;
- Cost effective investments in global and regional observing systems;
- Reduced access times to third party water data for forecasting models.

	BY 2022	BY 2025	BY 2030
KPI 2.1:	Six-hour gain in lead time for numerical predictions of rainfall, tropical cyclone intensity and streamflow.	Twelve-hour gain in lead time for numerical predictions of rainfall, tropical cyclone intensity and streamflow.	Twenty-four-hour gain in lead time for numerical predictions of rainfall, tropical cyclone intensity, and streamflow.
KPI 2.2:	Net Promoter Score of 60 or more for customers trust in the Bureau's baseline forecast and warnings services and data, measured through annual survey.	Net Promoter Score of 65 or more for customers trust in the Bureau's baseline forecast and warnings services and data, measured through annual survey.	Net Promoter Score of 75 or more for customers trust in the Bureau's baseline forecast and warnings services and data, measured through annual survey.



OBJECTIVE 3: AN EARTH SYSTEM NUMERICAL PREDICTION CAPABILITY: FULLY INTEGRATED ATMOSPHERE, OCEAN, SEA-ICE AND HYDROLOGY MODELS

The trend toward including numerous environmental couplings in atmospheric models will continue. These coupled models will be applied to inform responses to high-impact events and to ensure optimal watershed and ecosystem management. For example, surface variables like soil moisture will be more accurately predicted to help reduce bushfires and minimise the use of pesticides in agriculture. For the first time, we will see forecast models that balance the water and energy budgets at different scales. One of the major sources of error in hydrological predictions relates to uncertainties in predicted rainfall. This problem will be solved largely through the future development of regional convection-allowing NEWP models.

The land surface and the atmosphere interact through the global water cycle (exchanges of precipitation and evaporation) and control high-impact environmental events, for example floods and droughts, at regional to continental scales. Better representation of the water cycle will pave the way for more accurate prediction of floods and will better inform management of water levels in Australian catchments. This will also support operational prediction of floods, including coastal inundation, mapping of floodplains, planning of river diversions, and construction of new dams. The potential for new applications linking the environmental models and the economy is vast. These socio-economic benefits will be even more substantial with the increasing realism of the sub-models representing chemical processes, hydrology, the biosphere, and ocean circulation.

Significant advances have been made in atmospheric composition modelling in recent decades, supporting quality applications like smog and pollen warnings, forecasting of hazardous plumes from volcanic eruptions,

forest fires, oil and gas fires or dust storms. With a focus on the effects of weather on air quality, the next-generation NEWP models will increasingly examine the possible effects of atmospheric composition on predictive accuracy, especially by changing the radiation budget or ultimately by affecting cloud formation and precipitation. We will witness the development of near-real-time weather and chemical data assimilation to improve both weather and chemical weather forecasts. The retrieval of satellite data and direct assimilation of radiances will play a critical role in this regard. Some encouraging results are emerging such as the positive effect of ozone assimilation on wind fields that will improve the prediction of the Southern Hemisphere polar vortex.

The variability of the latter has important effects in some circumstances on high-impact weather like bush fires over eastern Australia. Ocean–atmosphere (and sea-ice and wave) interactions are one of the key challenges of weather and climate prediction on scales from days to seasons. For example, it has been demonstrated that the evolution of hurricanes on time scales of three to seven days can be significantly influenced by the presence of a coupled ocean in numerical prediction models. This and other needs will lead NEWP centres to add interactive components such as coupling to an ocean-sea-ice circulation model from day zero in weather prediction. The demand for atmosphere–ocean–ice forecasts will be amplified drastically in the coming decades as a result of increased socio-economic and strategic activities in the Antarctic.

3-YEAR TARGET	5-YEAR GOAL	10-YEAR VISION
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Initial implementation of future computing environment, Earth system coupling and efficient research to operations

Introduction of Next Generation Modelling System, capable of running on future HPC architectures

Nation-wide numerical full Earth system ensemble prediction system

DELIVERED THROUGH:

- | | | |
|--|--|---|
| <ul style="list-style-type: none"> • Establishment of a research to operations program; • Upgraded seasonal, ocean and wave predictions; • Prototype coupled model implemented for experimental numerical weather and ocean prediction; • Targeted development of exascale algorithms and tools and software refactored for graphics processing unit (GPU) accelerated computing; • Prototype Next Generation Modelling System components implemented and tested in collaboration with the UK Met Office; • Development of a climatology of aviation hazards (clouds, turbulence, icing) near Davis, Antarctica; • Development of a national river routing and riverine process model; • Advancing understanding of coupled hydrology-hydrogeology and human interactions, Earth system components leading to reduced biases, and space weather physics. | <ul style="list-style-type: none"> • Seamless atmospheric, ocean, land and hydrological modelling across time scales; • Antarctic coupled prediction systems, including sea-ice forecasting capability; • Transition of development and services to cloud computing; • Improved representation of physical processes in ACCESS from process study results; • Accurate coupled fire-atmosphere model; • New observational capabilities for Antarctica; • Significant reduction in sea surface temperature bias for Pacific Ocean, improved representation of the atmospheric boundary layer, improved intensity of tropical cyclones, Madden Julian Oscillation and climate variability. | <ul style="list-style-type: none"> • Fully coupled Earth system models, including hydrology, ensembles, with regional kilometre-scale, sub-hourly updating; • Use of information from throughout the water cycle to initialise coupled models; • Convection-allowing global model; • Significantly improved foundational Earth system components coupled for near-seamless information for all time scales; • Significant reductions in model biases in regions such as the Maritime continent and Southern Ocean; • An accurate space weather prediction system. |
|--|--|---|

Benefits

- Consistent multi-hazard information, for example, tropical cyclones and the associated heavy rain, flooding, inundation, wind, storm surge, waves, currents and tides from fully coupled systems;
- Improved public safety and community well-being and reduced property damage from severe weather events and hazards, including coastal flooding;
- Improved forecasts and projections for Australia and surrounding regions from enhanced understanding of processes in the Antarctic, Southern Ocean and Pacific regions, including space weather;
- Greater efficiency in model development and research to operations with coupled systems potentially decreasing the need for stand-alone domain models of the Earth system;
- Modelling systems that are aligned to adopt future HPC architecture;
- New technologies and HPC enable a flexible response to new software requirements.

	BY 2022	BY 2025	BY 2030
KPI 3.1	Five per cent reduction in forecast error for numerical prediction (including for high-impact multi-hazard events).	Ten per cent reduction in forecast error for numerical prediction (including for high-impact multi-hazard events).	Twenty per cent reduction in forecast error for numerical prediction (including for high-impact multi-hazard events).
KPI 3.2:	Implementation of model updates from the UK Met Office, relevant to Australia, within six months of becoming available at the UK Met Office.		



OBJECTIVE 4: SEAMLESS WEATHER AND CLIMATE

INSIGHTS: HISTORICAL OBSERVATIONS AND PREDICTIONS, FROM MINUTES TO DECADES

As our customers become more sophisticated and sensitive to our services there will be increased demand for the provision of consistent data in space, time and Earth-system domains. This will cross space scales from local to global and temporal scales spanning past historical records and model runs (hindcasts and reanalysis), to the present analysis, forecasts from hours to months ahead, and to decadal outlooks. For some customers this will mean just one timescale, for example, two-week outlooks for planning crop planting, while for others such as the energy sector or national security, a range of timescales will be required – from the past to the far future for a range of operational decisions through to infrastructure investment applications and future risk. Customers may demand the forecast for tomorrow and the outlook for next month, and an understanding of how that fits with climate variability.

Seamless products offer information that can be readily understood in the context of a range of timescales, for example, ‘is the weather tomorrow ‘typical’ of what we saw over the last decade?’ Seamless services mean consistent forecasts to users even where the source of the forecast model has changed – for instance, at the transition from ten-day numerical weather prediction to multi-week forecasts. The characterisation of uncertainty in the data, including from ensembles will be critical for risk-based services. Information will also be provided across the various Earth-system domains in a seamless and geophysically coherent way.

The complexity of NEWP systems will increase so much over the coming decades that a unified modelling approach for seamless climate and weather applications will be essential. A unified approach creates challenges but is greatly beneficial in terms of scientific research and cost-effectiveness. In addition to this unification trend, we will witness an increase in international collaborations devoted to developing and maintaining different components of the NEWP systems.

Examples are the Unified Model (UM) Partnership and the Nucleus for European Modelling of the Ocean (NEMO) general model of ocean circulation developed by a European consortium and used in many European countries and Australia. The socio-economic benefits of NEWP are so diverse, this approach promises to be a game changer for all aspects of the WMO’s Weather Enterprise (a global public-private partnership focused on monitoring, research, development, operations and services), and has potential to attract resource and infrastructure investments.

3-YEAR TARGET	5-YEAR GOAL	10-YEAR VISION
Development of initial improved and integrated models, datasets, services advice and products for the atmosphere and hydrology	Methods and systems established to produce seamless data, products, services and advice spanning weather, water and climate from minutes to decades	Seamless and targeted services informed by world-class weather, climate and social science to deliver data, products and services across all time scales (from past observations to multi-decadal climate projections)

DELIVERED THROUGH:

- | | | |
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| <ul style="list-style-type: none"> • Advice delivered to customers to aid decisions on climate variability and change and other impacts (for example, input into climate and disaster risk reduction frameworks, Intergovernmental Panel on Climate Change co-authorship); • Development of user focused products for sub-seasonal, seasonal and climate change timescales; • Seamless weather and climate forecasting spanning the gap between the next few days and weeks through seasons; • Near seamless national water prediction including national Hydrological Projections and short-term to seasonal water forecasting; • Production of national projections for Australia, delivered in partnership with other agencies; • Demonstration of the value of kilometre-scale high resolution climate projections as part of multi-model ensembles, over regions of major infrastructure; • Methods underpinning temperature and attribution service. | <ul style="list-style-type: none"> • Kilometre-scale climate reanalysis over Australia; • Seamless post processing of weather and climate model outputs to support consistent descriptions from days to decades; • Downscaled climate predictions and projections for extremes; • Improved advice to customers using new knowledge of weather and climate interactions (for example, impact of Sudden Stratospheric Warming on Australian climate) and new knowledge of climate sensitivity; • Temperature attribution service; • Improved understanding of climate variability and change across timescales to underpin improved services and effective communication. | <ul style="list-style-type: none"> • Social science considerations integrated into the design, development and evaluation of all services; • Seamless analysis and delivery of data from past records through to analysis, weekly forecasts, seasonal and multi-year prediction and multi-decadal projections; • Greatly enhanced uptake and influence of our climate forecasts and projections through increased customer confidence gained through our provided expert advice; • Improved understanding of variability and change in weather to climate, including extremes underpin improved services and effective communication; • Multi-element attribution service available (for example, temperature, rainfall and other extreme events); • Bureau research recognised nationally and internationally as world leading in weather and climate science. |
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Benefits

- Australians are better prepared for future weather and climate events through information which matches planning and decision horizons;
- National climate resilience and disaster risk reduction frameworks supported by outstanding climate science and services;
- Operational, tactical and strategic decisions in weather and climate sensitive industries and sectors are informed by state-of-the-art warnings, predictions, outlooks and projections, consistent from minutes to decades;
- Better understanding of and confidence in the impacts of climate variability and change, including change of the hydrosphere informing planning, investment and policy;
- Climate variability and change adaptation is well designed and leverages off latest assessments of past and future climate risk;
- Authoritative, reliable and resilient information on the future that can be used with confidence by the Australian community.

	BY 2022	BY 2025	BY 2030
KPI 4.1	Temporally and spatially consistent data spanning the full period from historical observation records, hindcast, reanalyses, forecasts, outlooks and projections for at least surface air temperature.	Temporally and spatially consistent data spanning the full period from historical observation records, hindcast, reanalyses, forecasts, outlooks and projections for at least two variables (surface air temperature and precipitation).	Temporally and spatially consistent and seamless data spanning the full period from historical observation records, hindcast, reanalyses, forecasts, outlooks and projections for at least five variables (surface air temperature, precipitation, soil moisture, wind and sea surface temperature).
KPI 4.2	Seventy-five per cent of customers satisfied with seamless/targeted products, measured through annual survey.	Eighty per cent of customers satisfied with seamless/targeted products, measured through annual survey.	Ninety per cent of customers satisfied with seamless/targeted products, measured through annual survey.
KPI 4.3	Five per cent year-on-year increase, over initial benchmark, in number of customers accessing seamless/targeted products, based on internet downloads/views.		



4. CAPABILITY REQUIREMENTS

4.1 LEVERAGING CAPACITY THROUGH ADVANCES IN COMPUTING AND DATA CAPABILITY

Computing architecture is evolving rapidly, and in just a few years HPC will be vastly different to what we operate on today. The next generation of numerical models will require significant changes to enable operation on these future platforms. To meet this challenge, the Bureau will invest strategically with our major national and international partners.

Complementing the Bureau's HPC systems, we will continue to utilise the National Computational Infrastructure (NCI) HPC for research and development activities, advancing the science that underlies the development of new and enhanced models.

Advances in computing capability, combined with increasing data volumes and data complexity, emphasises the importance of adopting effective data management practices. The Bureau *Data 2022 and Beyond* approach will provide the direction for data management improvements, with research and development contributing to the uplift of data capabilities. Data will be managed in line with Data Principles, and formal data lifecycle management processes will be implemented.

Technology improvements within the Bureau and our partnering agencies will enable efficient and timely access to third party data for rapid uptake in our systems.





4.2 ACCELERATING IMPACT VIA INTEGRATION

There will be an increase in predictions and observations for all components of the Earth system. There is no denying this global trend. Numerical weather prediction is no longer limited to weather; it includes all weather sensitive Earth system components. Work over the next decade will centre on combining all Earth system components in order to establish a NEWP system. As all NEWP forecasts will be probabilistic in nature, ensemble prediction system techniques will be used for all Earth system components. This will provide better numerical information for estimating the range of likely future weather and environmental conditions central to decision-making. Earth-system models including chemistry, hydrology, and other components, are expected to be applied in NEWP systems down to sub-hourly updating for regions and cities.

Modern NEWP models are complex scientific systems that require major international collaborations to be of a world class standing. The UM Partnership enables scientific and technical collaboration on a shared modelling system and maximises the return on our effort towards improved modelling capability.

The Bureau, along with CSIRO, is a foundation member of the UM Partnership – an international consortium with the UK Met Office, New Zealand National Institute of Water and Atmospheric Research, Korean Meteorological Administration and Indian Ministry of Earth Sciences. In addition, there are several associate partners, including key universities.

Maintaining and deepening our partnership with the UK Met Office is fundamental to our operational numerical prediction, post-processing, nowcasting and decision support capability. We share common data assimilation and modelling systems for numerical and coupled-seasonal weather prediction. Collaboration and inter-operability will enable efficient application of effort and advances in post processing and decision support methodologies and forecasting capability most relevant to each partner.

The timely and efficient transfer of research outcomes through to operational products and services will be important to this partnership. A streamlined research to operations process with a focus on numerical prediction systems will be implemented to more closely integrate science and development stages internally and ensure effective and efficient transfer to operations. Doing so will also enable rapid transition of upgrades between partners.



4.3 PARTNERSHIPS AND COLLABORATION

No nation can advance weather, climate and environmental prediction science in isolation. Collaboration ensures the Bureau and Australia benefit from national and international scientific, technological and operational developments and expertise, to achieve a resilient service, strengthen capabilities, build profile and reputation, foster collaboration, and serve the needs of Australians everywhere. The Bureau's national and international collaborations will continue to be important in tackling its research and development challenges.

We have deep and enduring bilateral and multilateral partnerships and intergovernmental cooperative relationships including the World Meteorological Organization (WMO), International Civil Aviation Organization (ICAO) and the Intergovernmental Oceanographic Commission (IOC). Through the WMO we participate in the World Weather Research Program (WWRP), the Working Group on Numerical Experimentation (WGNE), and the atmospheric composition research program of the Global Atmosphere Watch (GAW), in addition to co-sponsoring the World Climate Research Programme (WCRP). We also participate in global observing efforts (particularly in the context of the WMO Integrated Global Observing System (WIGOS), via our national and regional activities. In return we have access to the global network of observations that underpin our data.

As well as the key partnership with the UK Met Office, the Japan Meteorological Agency, Korea Meteorological Administration, US National Oceanic and Atmospheric Administration, CSIRO, Geoscience Australia, Australian Antarctic Division, NCI and National Collaborative Research Infrastructure Strategy (NCRIS) facilities, in particular the Integrated Marine Observing System, are all partners of consequence for the Bureau.

The Bureau enjoys long standing productive partnerships with many Australian universities and research institutes and associated Centres of Excellence and we are developing an Academic Partnership that will further support strategic scientific and research collaboration.

Partnering with private industry will also be an important aspect of realising future benefits. Advancements in NEWP will massively expand the number of potential applications of weather and climate modelling systems. This will revolutionise cooperation and partnerships between the public, private and academic sectors. Collaboration will be crucial for advancing the required science and technology, through high-risk and upstream research, and in training and developing the next generation of highly qualified personnel. We are now seeing the private sector operate their own NEWP systems for targeted applications and customer specific requests. These systems depend, however on the public and academic sectors for innovation, with advancements in NEWP science strengthened through collaboration between the public, private and academic sectors.

4.4 DEVELOPING OUR CAPABILITIES FOR THE FUTURE

Our people are our most valuable resource. We will continue to develop and support our people whilst also building the pipeline for new talent, skills and expertise into the organisation to support our research and development direction.

A workforce plan will map the development of skills and expertise required into the future, ensuring strategic alignment of our workforce to delivery of this Plan. The rapid growth in Earth system model sophistication, data volumes and HPC complexity will necessitate a significant expansion in staff capability for multidisciplinary Earth sciences, data scientists, software engineers and scientific computing specialists.

Some capability areas will be developed through partnering with universities to support students, post-doctoral fellows and academics. Such areas of focus will include Earth observations, data assimilation, machine learning, social sciences and data management.

We recognise that diversity promotes innovation and builds greater team effectiveness and we will continue to encourage flexibility and diversity at all levels.

Career planning and structured development pathways will be central to supporting our staff. We will provide training and development opportunities to enrich and empower our people, not only in science and technology domains, but crucially, in areas including leadership, communication and teamwork. Development pathways will be linked to the progression and advancement of our services, supporting emerging thinking, active innovation, exploration and discovery. We will facilitate mobility of staff between research and development areas with greater operational and leadership roles, developing our future leaders and providing enriching career pathways.

4.5 INNOVATION, EXPLORATION AND DISCOVERY

Emerging technologies and developments have the potential to enhance and disrupt our research and development capabilities and the Bureau's operations. Rapid and informed uptake of new approaches within our research and development areas will be accelerated through early development of capability and access to supporting computing resources.

Through these investments, we will enhance our capability, expertise and understanding of emerging technologies, such as artificial intelligence and machine learning, and future computing, such as cloud computing, and next generation modelling with the aim of guiding, informing and influencing our research and development implementation. When appropriate, we will partner with national and international research centres to foster innovation and experimentation and deliver our research in engaging and innovative ways. The knowledge gained through this will ensure that our programs are delivering the right research outcomes using the best available tools and technologies.

Within this discovery and exploration environment, new techniques and approaches to research, development and delivery will be developed, trialled and tested in line with an enterprise innovation framework. This will include creating a testbed environment as an integral part of the transition of research to operations process, accelerating the transition of experimental systems and concepts to operations, and enabling greater exploration with customers, of potential future Bureau products and services.

5. BENEFITS

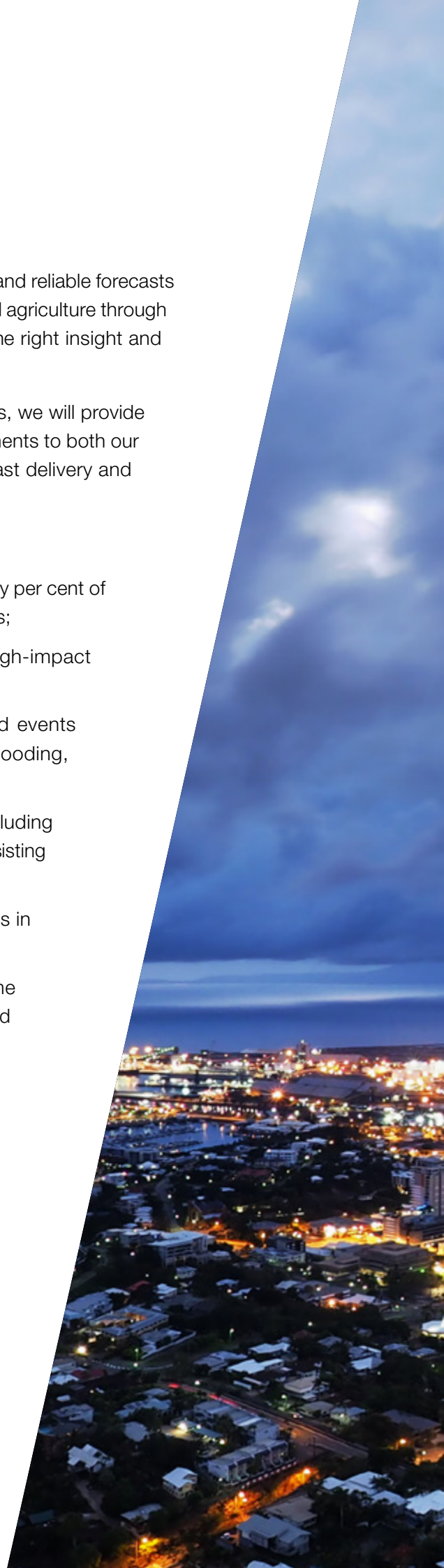
In addition to saving lives through mitigation of hazards, accurate and reliable forecasts create financial benefit for industries such as energy, transport and agriculture through avoided losses and enhanced opportunities for revenue. With the right insight and decisions, our communities, economy and sectors will prosper.

Through delivery of our four research and development objectives, we will provide significant benefits to our customers driven by focus on improvements to both our underpinning numerical prediction capabilities and to our forecast delivery and services based on customer needs.

In future our customers should experience:

- Improved forecasts of high-impact weather events for the ninety per cent of the population who live in and around the nation's largest cities;
- Greater forecast accuracy in both the location of where high-impact weather events happen and the timing of when they occur;
- Greater lead time for warnings of extreme and multi-hazard events including heatwaves, severe thunderstorms and coastal flooding, enabling timely mitigation actions;
- More accurate weather predictions further ahead in time, including one day ahead for weather and two days ahead for flooding, assisting planning and preparedness;
- More frequent and timely forecast updates driven by advances in automation and technological advances; and
- Seamless and consistent weather and climate data across time and space, offered probabilistically, enabling improved risk-based decision-making.

These improvements will be focussed on delivering the Bureau's Strategy and contributing towards the goals of zero lives lost due to meteorological and oceanographic hazards and the provision of billions of dollars of additional economic value to the nation.





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