Final report

Forewarned is Forearmed (FWFA): equipping farmers and agricultural value chains to proactively manage the impacts of extreme climate events

Project code: B.CCH.8100

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Date published: December 2022

PUBLISHED BY
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Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Abstract

Australian producers operate in one of the world's most variable climates. Climate variability and extreme climate events are key drivers of annual agricultural production and income.

Forewarned is Forearmed (FWFA) is a national project that supports producers and the agriculture sector. It prepares producers with information and tools forewarning of extreme climatic events on multi-week and seasonal timescales. The project aims to reduce the impact of extreme climate events on farm, and on business profit.

The Bureau of Meteorology (BoM) has developed and delivered new forecasts of extremes for multi-week and seasonal timescales. The forecasts are based on the Bureau's seasonal forecast system and are available on the Bureau's public website for the benefit of all agriculture.

This services outcome was built on a solid foundation of research and development, including evaluation of producer and advisor needs, underpinning science to understand the predictability of extremes and the capability of the forecast system, and a co-design approach with project partners and Industry Reference Groups to develop and design the new forecasts.

These new products have provided agriculture with the first ever forecasts of rainfall and temperature extremes for the weeks to seasons ahead. Warning of these events increases ability to manage climate risk.

Executive summary

Background

In Australia, extreme climate events and climate variability are amongst the largest drivers of annual agricultural production and income. However, prior to the Forewarned is Forearmed (FWFA) project there were no warnings of these extremes beyond the 7-day weather forecast. Consequently, there was a significant gap in the capacity of agriculture to mitigate and plan for events such as a very wet season, or a heatwave in the coming weeks. The FWFA project aimed to start filling this gap.

Working with research partners and producers, the Bureau of Meteorology (Bureau) would develop and deliver forecasts of the likelihood of climate extremes on multi-week and seasonal timescales, using the state-of-the art prediction system, ACCESS-S. Research partners would use Bureau outputs and work directly with producers to interface the forecasts to agricultural decision-making, including developing risk management strategies.

FWFA is supported by funding from the Australian Government as part of its Rural R&D for Profit program in partnership with rural Research and Development Corporations, commercial companies, state departments and universities. The project is managed by Meat & Livestock Australia.

This report focusses on the Bureau of Meteorology component of the FWFA project.

Objectives

The objectives for the Bureau's component of the project were to:

- Evaluate producer needs for forecasts of climate extremes.
- Conduct underpinning scientific research to understand the large-scale drivers (e.g., *El Niño*) of extremes, and the strengths and weaknesses of the ACCESS-S forecast system.
- Conduct research and development to improve the forecast model.
- Develop a large set of experimental forecast products.
- Deliver a sub-set of five new forecast products on the Bureau's public website, for the benefit of all agriculture.

All objectives were achieved.

Methodology

- Conduct workshops with Industry Reference Groups to provide insight into key weather and climate risks and the need for forecasts of extremes.
- Examine observations and model data to understand the predictability of extremes and the capability of the forecast system.
- Identify key errors in the model and implement improvements.
- Develop a range of heat, cold and rainfall experimental forecast products from ACCESS-S.
- Make experimental products available on a research web server for trial and feedback.
- Obtain feedback on the experimental products from project partners and reference groups of users.
- Select a sub-set of five products and refine them based on feedback to become available as official Bureau products.

Results/key findings

A key outcome of the project is the five new forecast products available on the Bureau's website. These represent a significant enhancement of the climate outlooks service, providing agriculture with critical information of upcoming extremes.

The end-to-end approach of the project − spanning underpinning climate science, forecast product development, engagement with users, and the delivery of a new service − enabled efficient feedback between the different components, facilitating a faster and more effective outcome of delivering practical and useful information to decision-makers.

Benefits to industry

The project has delivered a state-of-the-art forecasting service for extreme climate events via the Bureau website. The project has improved the quality of climate and weather information available to the agriculture sector. This will improve decision-making, resilience and proactive planning for managing climate variability and change.

Future research and recommendations

The project leaves a legacy of:

- Strong networks between researchers from different institutes and agricultural Research and Development Corporations (RDC's).
- A large set of experimental forecast products.
- A large body of scientific knowledge.
- Key insights into agricultural decision-making and the use of forecast information.

Future research, development and extension should leverage off and build on these established relationships, knowledge and insights to further refine and enhance the quality and interpretability of forecast information available to the agriculture sector. The experimental products are a key resource for future projects.

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1. Background

1.1 The need and gap

Australian farmers and agribusiness operate in one of the most variable climates of any country in the world. Extreme climatic events (such as heatwaves, frost and heavy rainfall) and climate variability are amongst the largest drivers of annual agricultural production and income (Love 2005; Howden et al. 2007; Stokes and Howden 2010). Several studies have concluded that further research is required to provide farmers with improved capacity to manage extreme climate and weather events (e.g., Cullen et al. 2009; Cullen et al. 2012; Eckard 2016).

Considerable use is made of existing weather forecast warnings (days 1–7) for extreme events, such as heavy rainfall and heatwaves. However, there is a significant gap in warnings of these extremes beyond 7-days and out to seasons ahead. Consequently, there is a significant gap in farmer's capacity for short-term proactive mitigation and response planning strategies to upcoming extremes. The FWFA project's key aim was to start filling this gap.

1.2 The approach

The approach was that the Bureau, working with several research partners, would develop and deliver forecasts of the likelihood of climate extremes on multi-week and seasonal timescales — beyond the 7-day weather forecast. The products would be focused on heat, cold and rainfall extremes, for example, "what is the likelihood of having a decile 10 rainfall this spring?"; "what is the chance of having a heatwave in the week after next?"; "what is the chance that the upcoming month will be extremely hot?"; "what is the likelihood of having more heavy rainfall events than usual in the upcoming fortnight?". This would provide farmers with the first ever forecasts of climate extremes in the weeks to seasons ahead.

Project partners include agricultural climate and systems analysis researchers and extension experts with expertise in the dairy, beef, sheep, grains, sugar and wine industries. Partners would use Bureau outputs and work directly with farmers and farm consultants to interface the forecasts with agricultural decision-making, including developing risk management strategies.

The national project includes collaboration between eight RDCs (Meat & Livestock Australia, Grains RDC, Dairy Australia, Agrifutures Australia, Sugar Research Australia, Cotton RDC, Wine Australia, Australian Pork Limited), and had user-reference groups encompassing six industries (dairy, beef, sheep, grains, sugar and wine). While these are the main industries where direct producer involvement occurred, the outcomes of the project will extend into other agricultural industries, and beyond.

1.3 A new and innovative venture

Forecasting weather and climate extremes is a complex science, and the Bureau is one of the world leaders in this area (e.g., Vitart et al. 2018). No other country has developed a suite of products such as those proposed and developed for FWFA. The research, development and service delivery is at the leading edge of international R&D. For example, the Bureau was invited to present on FWFA project results and learnings at the Third World Meteorological Organisation (WMO) Workshop on Operational Climate Prediction (20-22 September 2022, Lisbon) in the session on "Tailoring of climate prediction products and information to meet user needs on sub-seasonal to decadal timescales" (Hudson 2022, see Appendix 8.2).

Communicating and applying climate forecasts to decision-making is an ongoing challenge, particularly given their probabilistic nature. Some of these challenges were addressed by the Round one Rural R&D for Profit Project "Improved use of seasonal forecasting to improve farmer profit". FWFA has built on that understanding. However, the key focus in FWFA is on interfacing forecasts of extremes (rather than average or median conditions) to agricultural decisions.

While structured industry engagement in projects is not new, FWFA scales this approach at a level rarely seen in Australian agriculture – with 14 project partners working together in an end-to-end approach, spanning underpinning climate science, forecast product development, engagement with users, and the delivery and extension of a new service.

The sections below will report on the Bureau's key work packages, as follows:

- Work Package 1 has two components:
  - Evaluate user needs to inform research needed for extreme event forecast products.
  - a) Underpinning science and b) improving the forecast system.
- Work Package 2: Develop forecasts of climate extremes for weeks to seasons ahead and then deliver a subset of five as a Bureau service.

2. Objectives

Overall objective: The research and forecast product development will deliver a state-of-the-art forecasting service for extreme climate events delivered via the Bureau website. **(Achieved)**

2.1 Work Package 1: User needs and underpinning science

- Report synthesising user needs for forecasts of weather and climate extremes on multi-week to seasonal timescales.
- Documented set of extreme events which had significant impact on key agricultural sectors and can be used for case studies of predictability, system improvement, product development, risk management toolkit development, communication and education material, as well as future studies.
- Reports/publications on understanding the drivers and predictability of heat, cold and rainfall extremes.
- Reports/publications on understanding model errors contributing to the ability to predict extremes.
- Reports/publications on ACCESS-S improvements that reduce model systematic errors.
- Improvements to ACCESS-S to reduce systematic biases.
- Presentations at workshops, reference groups, Community of Practice and conferences.

All objectives were achieved.

2.2 Work Package 2: Forecast product development and delivery

- Multi-week and seasonal climate extremes Bureau Service to the public: Five products, that have sufficient utility and accuracy, will be delivered as a service via the Bureau of Meteorology website.
- A large set of experimental forecast products.
- Reports documenting the operational products.
- Reports documenting the feedback on the experimental products.
- Presentations at workshops, reference groups, Community of Practice and conferences.
- Recommendations for future product development and delivery.

All objectives were achieved.

3. Methodology

3.1 Work Package 1: User needs and underpinning science

3.1.1 Evaluate user needs to inform research

This component was done in close collaboration with the researchers in Work Packages 3 and 4. Methodology was as follows:

- Define key regions, extremes indices, critical timescales (weeks/months/seasons) and times of year by:
  - Holding workshops with the industry reference groups (established by Work Package 3) of producers and advisors from dairy, beef, sheep, grains, sugar and wine industries to define project outputs.
  - Reviewing past reports on industry forecasting needs (e.g., from the BoM Ag White Paper project and Rural R&D for Profit Round 1 seasonal project).
  - Seeking input via the FWFA Community of Practice.
- Identify a set of extreme events that occurred during 1981-present, which had significant impact on agricultural sectors and can be used for case studies of predictability, system improvement, product development, risk management toolkit development, communication and education material, as well as future studies. Note: this is a resource from which to select cases for particular studies, as appropriate.

3.1.2 Forecast system research, development and evaluation

<u>Underpinning science:</u>

Methodology aims at understanding the large-scale climate drivers (e.g., *El Niño*, Madden-Julian Oscillation (MJO)) of extremes over Australia using observations and then examining their depiction and prediction in the forecast system, including the use of case studies.

This fundamental scientific understanding provides an appreciation of the strengths and weaknesses of the forecast system and guides the development of forecast products, as well as improvements that can be made to the model.

Methodology comprises:

- Understanding the sources of predictability of different extremes over Australia. This is investigated using observations, by diagnosing relationships between a given extreme and the large-scale low-frequency variations of the atmosphere or ocean that act to pre-condition the occurrence of the extreme (e.g., teleconnections driven by the MJO).
- Examining the depiction and prediction of these large-scale pre-conditioners in the forecast system. For example, the existence of *El Niño* conditions has a significant effect on the expected number and pattern of heatwaves in a season. Therefore, the ability to simulate and predict *El Niño* with ACCESS-S will influence the ability to predict heatwaves.
- Evaluating case studies of particular events.

Improving the forecast system (sub-contract to Monash University)

The focus here is on improving ACCESS-S to give better extreme event forecasts.

Methodology comprises:

- Identifying and understanding the key model systematic errors present during the extreme events in the hindcast period.
- Identifying pathways to model improvements to reduce systematic errors.
- Modifying the model's atmospheric convection parameterisation and running test simulations to investigate the impact on the representation of extremes.
- Integrating model improvements into the ACCESS-S system (note: the model version that these changes are implemented in will not be operational on the timescale of this project. They will contribute to a future version of ACCESS-S).

3.2 Work Package 2: Forecast product development and delivery

Methodology to develop and deliver forecasts of climate extremes for weeks to seasons ahead by:

- Developing a large set of experimental forecast products from ACCESS-S related to heat, cold and rainfall-based extremes. The development of the forecast products will be defined during the project in consultation and feedback from project partners and users (particularly those in the Industry Reference Groups).
- Making the experimental products available on a research web server to partners and their users for trial and feedback (interaction with Work Package 3) and modifying these based on feedback. The experimental forecasts will update in real-time.
- Including both map-based and location-specific products. For the latter, locations for trialling the products will be decided in consultation with project partners and Industry Reference Groups.
- Transitioning of the experimental products from ACCESS-S1 to the upgraded seasonal prediction system, ACCESS-S2.
- Selecting a subset of five products (in a staged approach) to become official, operational Bureau products and to be delivered to the public via the Bureau's website. The products will be of broad utility across industries (i.e., not highly tailored for a specific industry). The choice of the five products will be informed by industry engagement and will be a whole-of-project decision, ratified by the Investor Advisory Group.

- Refining the appearance and interpretation of the selected products prior to them being made operational (this includes accuracy and climatology information which will be available on the website). This will be driven by feedback from project partners and Industry Reference Groups.
- Developing the front-end of the website to host the new products and display them in accordance with agreed visualisation and functionality, including supporting information.
- Ensuring that the product generation code is refined and optimised to ensure that the process of viewing the products runs smoothly and expeditiously across the entire Australian continent for the location-specific products so as not to cause delay.
- Ensuring the product generation code has been peer reviewed, has suitable unit tests, is thoroughly documented, has a code-history archived and meets Bureau computing requirements for deployment into the Bureau production environment.
- Migrating the code into the Bureau's production supercomputing environment, while ensuring all data-feeds and transfer processes are robust and maintain the agreed level of service.
- Delivering the operational forecasts on the Bureau public webpage.

Note: Engagement with users is key. The Industry Reference Groups and project partners will help define the forecast products for development, thereby ensuring that they are well targeted and meet the needs of farmers in each industry. Ongoing engagement with these groups throughout the project provided feedback to the project team, and guided product development and service delivery. In addition, the BCG Community of Practice brought together project teams and key advisors across Australia via regular webinars to obtain feedback and to promote understanding of the experimental and operational products.

4. Results

4.1 Project outcomes

4.1.1 Introduction

A key outcome of the project are the new forecast products available to the Bureau's long-range forecast suite. These represent a significant enhancement of the service (http://www.bom.gov.au/climate/outlooks) − providing users with critical information to support decision-making.

This services outcome has been built on a solid foundation of R&D, with key results are provided in the sub-sections below.

4.1.2 Work Package 1: User needs and underpinning science

Evaluate user needs to inform research

Key outcome:

- *Increased understanding of user needs for forecasts of extreme weather and climate events on multi-week to seasonal timescales.*

Nine Industry Reference Group workshops were held between October 2017 and September 2018.

The workshops were attended and coordinated by Bureau project staff together with the Work package three researchers:

- Sugar industry, Townsville, 26 October 2017
- Red Meat industry, Charters Towers, 27 October 2017
- Red Meat industry, Longreach, 7 November 2017
- Red Meat industry, Rockhampton, 8 November 2017
- Northern Red Meat and Sugar industry Reference Groups, webinar, 11 April 2018
- Dairy reference group workshop, Melbourne, 7 June 2018
- Southern Red Meat reference group workshop, Melbourne, 22 June 2018
- Grains reference group workshop, Canberra, 17 August 2018
- Wine reference group workshop, Adelaide, 13 September 2018

The purpose of the workshops was to gather insights into the main weather and climate risks and the utility of extreme climate forecasts in the respective industries. Topics covered included: primary weather/climate risks; key weather-related decisions; how might a forecast help; what actions could be taken in response to a forecast; how far in advance is information required to be able to act; what are the critical times of year.

In addition, the workshops were used to identify cases of extreme events that had a significant impact on agricultural industries participating in the project. A spreadsheet was prepared that documented these events. The purpose of the spreadsheet was to identify possible case studies for scientific analysis, risk management, education and communication. In terms of the scientific analysis, recent events that occurred during the project (in 2019 and 2020) were in the end used for the case studies.

A user needs synthesis report was prepared (Shelley, 2018; See Appendix 8.1). The report drew together information from RRD4P Round 1 projects, information from the Reference Group workshops and additional insights from work with stakeholders as part of the Bureau Agriculture Program's regular business. This report synthesizes decision points and forecasting needs of the Red meat, Grains, Wine, Dairy, Sugar, Rice, Cotton and Pork industries in managing rainfall, heat and cold weather and climate extremes in Australia. It focuses on defining management actions, key regions, timescales (weeks/months/seasons) and lead times, and times of year where agricultural businesses are most impacted.

Capturing insight into user needs was an ongoing activity throughout the project.

Underpinning science

Key outcome:

- *Increased understanding of the drivers and level of predictability of weather and climate extremes. This scientific knowledge underpins the development and communication around an extremes service*

This science is critical for us to understand both our forecast system and how the main climate drivers are related to extremes over Australia. The understanding underpins our seasonal climate service and is critical in helping us to understand the real-time forecasts. It informs the narrative that goes out to users, and the confidence that we might have in the forecasts for a given situation.

For example, our stratospheric research has demonstrated for the first time the role that Antarctic polar vortex variations may play in predicting climate extremes over Australia up to a season in advance. The culmination of this work includes two very high-profile publications in the international science community, in Nature and Nature Geoscience. In addition, all the science came to bear in winter-spring 2019, when the air above Antarctica warmed unusually and became a driver of the extremely hot and dry conditions and catastrophic fire danger that we experienced in spring of that year. Not only were we able to forecast it, but the science that had been done gave us confidence in the forecasts and an understanding of what was going on, which we were able to communicate. The communication through public mainstream media and its possible implications for eastern Australian spring climate was very effective and brought a lot of attention to the progress we are making in predictive capability that was being supported by FWFA. A Conversation article (see Appendix 8.3) on the 2019 event, written by FWFA researchers, has received over 700 000 views.

We have shown the following with regards to rainfall, heat and cold extremes:

Rainfall:

- The skill of ACCESS-S2 in predicting rainfall bursts across northern Australia is highest in the first week of the forecast and decreases with lead time. Skill is generally stronger and more significant over Queensland than the Northern Territory and northern Western Australia in the second week of the forecast between October to December. The peak skill months, in terms of magnitude and area of significance, occur from January to March, with the highest skill scores in March across all lead times from weeks 1 to 4 (Cowan et al. 2022, see Appendix 8.1).
- ACCESS-S1 performs well for some extreme rainfall indices on lead-times up to 1 month. Forecast performance is highest in autumn, winter and spring and greater in the north and interior of the continent, particularly in the dry season, than elsewhere. ACCESS-S1 also captures the broad pattern of relationships between modes of climate variability and rainfall extremes that are observed. These results suggest that ACCESS-S1 may be used to produce outlooks for some rainfall indices, such as the number of wet days and the intensity of the wettest day, for the month ahead (King et al. 2019, see Appendix 8.1).
- Many areas of Australia received near average to severely below average rainfall in spring 2020, particularly during November, due to (a) the ocean surface to the north of Australia being not as warm as expected, (ii) an early decay to the negative phase of the Indian Ocean Dipole (IOD) in October, and (iii) the emergence of the suppressed phases of the MJO in November. ACCESS-S1 accurately predicted the strength of *La Niña* but overpredicted the ocean warming to the north of Australia and underpredicted the strength of the November MJO event, leading to an overprediction of the spring and November rainfall (Lim et al. 2021b, see Appendix 8.1)
- ACCESS-S1 successfully captures the relationship between extreme rainfall and the MJO, although the signal is usually weaker than observed, especially across the far north during the summer season. In general, there is enhanced forecast skill for predicting extreme weekly mean rainfall across much of Australia at times when the MJO is strong, compared to when it is weak, during spring and summer out to 3 weeks lead time (Marshall et al. 2021, see Appendix 8.1).

Heat:

- The weakening of the polar vortex is usually accompanied by a negative Southern Annular Mode (SAM) and extreme warm conditions in eastern Australia, as happened during October 2002. A case study indicated that the warm conditions were underpredicted in ACCESS-S1. This was attributed to the model using prescribed climatological monthly mean ozone. In model experiments that included observed monthly varying ozone, the warm conditions were predicted well. Polar stratospheric ozone variations are thus shown to be an important potential source of seasonal timescale predictability. Future model development should focus on including time-varying ozone concentrations in the model (Hendon et al. 2020, see Appendix 8.1).

- Unusually strong weakening of the stratospheric polar vortex substantially increase the chance of hot and dry extremes and fire weather across subtropical eastern Australia from spring to early summer. These conditions in the polar stratosphere led to a negative SAM. The long timescale of the polar vortex variations means that the increased chance of early-summertime hot and dry extremes and wildfire risks across eastern Australia may be predictable a season in advance during years of vortex weakening (Lim et al. 2019, see Appendix 8.1).
- The Southern Hemisphere stratospheric vortex weakening in spring 2019 was the strongest ever observed. The resulting record-strong negative SAM was a primary driver of the extreme hot and dry conditions over eastern Australia and severe wildfires in late spring. ACCESS-S1 skilfully predicted the significant vortex weakening and subsequent development of negative SAM from as early as late July 2019 (Lim et al. 2021c, see Appendix 8.1).
- The MJO causes strong and significant warming, including extreme heat, across southern Australia when it is active over the Indian Ocean and Maritime Continent (phases 2,3 and 4). The heating appears in the vicinity of a deep high-pressure anomaly which brings warmer air to south-western Australia while promoting shortwave radiative heating in the southeast. The MJO is a source of multi-week predictability of springtime heat over southern Australia in ACCESS-S1 at lead times of 2–4 weeks, yet there remains room for improvement. (Marshall et al. 2022, see Appendix 8.1)

Cold:

- Extreme low minimum temperatures (Tmin) occurred across northern and eastern Australia in September 2019 during the positive IOD and central Pacific *El Niño* due to an anomalous high pressure over the Great Australian Bight. This moved cold air across eastern Australia and reduced cloud cover over northern and eastern Australia, enhancing radiative night-time cooling. ACCESS-S1 had difficulty predicting the anomalous high pressure in the Bight and the cold anomalies in the east due to mean state biases in sea surface temperature and rainfall in the tropical Indian and western Pacific Oceans (Lim et al. 2021a, see Appendix 8.1).
- The MJO during wintertime causes a large region of below normal minimum temperature (Tmin), including extreme cooling, across much of Queensland during MJO phases 6 and 7. This is due to cold continental air movement from the interior of Australia and reduced lower atmospheric humidity, which results in enhanced night-time cooling. Although ACCESS-S1 can predict the MJO relationship to temperature during winter, this does not translate into enhanced forecast skill. This is thought to be due to deficiencies in the soil moisture initialisation in ACCESS-S1 (Wang and Hendon 2020, see Appendix 8.1).

In summary, this research has shown how:

- Modes of climate variability (climate drivers) such as variations in the stratospheric polar vortex, *El Niño*, the MJO and the SAM influence climate extremes over Australia.
- The skill for predicting extremes varies strongly by location, season and forecast lead-time.
- Timescales of predictability vary for different climate drivers.
- Climate drivers influence forecast skill for rainfall and temperature extremes over Australia.

- Model errors and initialisation errors impact the prediction skill of multi-week to seasonal extremes over Australia.

This work has provided much-improved understanding of climate driver impacts on Australian climate extremes and their real-time prediction using the ACCESS-S forecast system. This feeds into regular climate briefings to project partners and stakeholders, industry and government. An example of such has been the FWFA-funded monthly Bureau Climate Science updates: Andrew Watkins, Harry Hendon, Andrew Marshall and/or Matthew Wheeler provided monthly climate briefings on the current state of the climate and upcoming conditions to the Birchip Cropping Group's Community of Practice (note, this was separate from the FWFA COP seminar series).

Improving the forecast system

Key outcome:

- *A new, improved model component that enhances or suppresses convective rainfall by a sea-land breeze scheme.*

There were two components of work which led to the development of a new sea-land breeze scheme for the model:

a) Analysis of model errors during very hot summers and how they might be reduced

This work focussed on how well the ACCESS-S model simulates hot summers. Results indicated that:

- There is a strong *El Niño* influence on occurrence of extreme maximum temperature seasons (top 20% events).
- When hot summers are observed, the ACCESS-S model underestimates the average maximum temperature and generally has a cold bias over parts of Australia.
- The nature of the error differs if the extreme seasons are defined for the whole of Australia compared to those defined as extreme for only the south-eastern region. This bias has serious implications for the other variables, especially the precipitation rate over Australia, and the Pacific and Indian Oceans.
- ACCESS-S fails to accurately simulate the increased rainfall over north-eastern Australia and the adjacent ocean during heat extremes over the south-east.

The investigation showed that ACCESS-S produces forecasts of hot summers but not necessarily for the right reasons. The model fails to simulate the observed connection of hot summers in the south-east that occur when it is wet in the north of Australia, thereby missing an important mechanism that can lead to heatwaves.

The next goal of this work was to identify regions where model improvements could positively impact the simulation of hot summers over Australia. To achieve this, we analysed a suite of model simulations where parts of the globe are nudged back to observations. The main consequence of the nudging is that model errors in the nudged regions are strongly reduced. The impact of reducing these errors can then be examined for those parts of the globe where the model is allowed to evolve freely.

Analysis of the nudged runs showed that model errors over Australia in hot summers can be improved by reducing model errors in the tropics. In particular, the tropical area north of Australia plays a particularly important role in the simulation of hot summers over Australia. A reduction of model errors within these areas will likely contribute to improvements over Australia. Based on these results our pathway to improving the simulation of hot summers over Australia is the development of a coastal rainfall scheme that aims to reduce model errors over the Maritime Continent (mixture of land and seas straddling the equator between the Indian and Pacific Oceans north of Australia).

b) Development of a sea-land breeze scheme to enhance or suppress convective rainfall

The analysis above demonstrated that systematic errors in rainfall over the Maritime Continent negatively affect the simulation of hot conditions (especially in summer) over south-east Australia. This was associated with a lack of convection (rainfall) over the often-complex topography of the many islands that constitute the Maritime Continent. A key reason for this shortcoming is the inability of the model to resolve sea-breeze circulations that are responsible for a significant fraction of the rainfall in this region.

In response, we developed a parametrisation for the enhancement and suppression of convective rainfall by a sea-land-breeze system in the global atmospheric model of ACCESS-S. Sea-land breezes are not currently present in the model and as such their impact on convective rainfall is not represented. This leads to rainfall biases in coastal locations.

The parametrisation makes use of the model's land-sea distribution to calculate a parameter that indicates the existence and strength of sea-breezes along model coastlines. This parameter can then be used to modify the likelihood of convection along coastlines.

The model experiments undertaken during the development indicated encouraging results. The new sea-breeze parameter prediction is sound and follows the diurnal (day–night) cycle well. Resulting rainfall is well represented in wet coastal regions and dry sea-breezes do not produce spurious rainfall for regions that are affected by them e.g., over Western Australia. Large-scale synoptic rainfall events suppress sea-breeze evolution in the model as they do in the real world.

The sea-land-breeze scheme has been stored in the code repository for the UK Meteorological Office (Met Office) model and been handed to the Bureau for inclusion in their development of the next-generation seasonal prediction system in collaboration with the Met Office.

The final stage of testing the full effect of the new scheme was delayed by a longstanding computational issue introduced by the parallelisation of the model code. The issue required further assistance from the Met Office. Additionally, due to COVID-19, the postdoctoral researcher who carried out the work left Australia to be reunited with their family in Europe. At that late stage in the project, it would have been very difficult to recruit the skills required in time to carry out remaining testing. For these reasons, the final Milestone was partially achieved. The work was handed over to the Bureau to be incorporated in future model development plans beyond the FWFA project.

This work was a very significant foundation for catalysing ongoing model development work in this area between the Bureau and the UK Met Office. The Bureau has since picked up this work as part of their core model development, has recruited a new researcher and is now actively working with the Convection Team at the Met Office on the inclusion of the sea-breeze scheme in the new state-of-the-art convection scheme being developed for the next global model configuration. Significant progress has been made in this area (e.g., White et al. 2022).

4.1.3 Work Package 2: Forecast product development and delivery

Key outcomes:

- *New extreme climate forecasts for use in agricultural decision-making.*
- *Enhanced Bureau service to the agricultural sector.*
- *A large set of experimental forecast products, which are now available to feed into future initiatives.*

- *Established collaboration pathways with research partners and industry for future and ongoing forecast product development.*
- *Increased uptake of seasonal prediction products and services for agriculture (facilitated by the linkage to partners undertaking applications research, the industry reference groups and extension and training).*

Experimental Forecast Products

The project involved extensive consultation with industry reference groups and project partners during the forecast product development to provide ideas for product development and to gain feedback on the appearance, utility and interpretation of the experimental forecast products.

A large set of experimental forecast products:

A research project website for the experimental forecast products was developed (http://poama.bom.gov.au/project/fwfa/index.html) (Fig. 1). This website is password protected and available to project partners, Industry Reference Groups and others (at the discretion of project leaders). It will continue to be available until June 2023.

Details are as follows:

- The experimental forecasts are hosted on a special web interface (Figure. 2) which was designed for the project to enable viewing of the forecasts in the trialling and testing phase.
- The forecasts are updated daily in real-time.
- More than 27 products were developed during the project. Table A1 lists the experimental products (Appendix 8.4). Some products are more general, and applicable to rainfall, heat and cold extremes, such as the Decile Bars (i.e., counted as one product). Whereas some are specific to either rainfall, heat or cold extremes, such as the rainfall probability of exceedance curves. The product development was done in a co-design approach with partners and users, with the aim of eventually converging on the final products to be made operational. The experimental products were developed in phases over a few years, with feedback gathered at various intervals.
- Each product is accompanied by an "explainer" which describes the product and aids interpretation for the trialling phase (e.g., Fig. 3).
- The location-based products were tested and trialled using ~560 stations (Figure. 4). The location of these stations was determined in consultation with project partners and industry reference groups. It was vital for the trialling of the products that producers were able to relate the chosen forecast location to conditions on their own farm. (Note that the final operational products are available for any location in Australia on a 5km grid).

Figure 1: A screenshot of the FWFA research project website for the experimental products

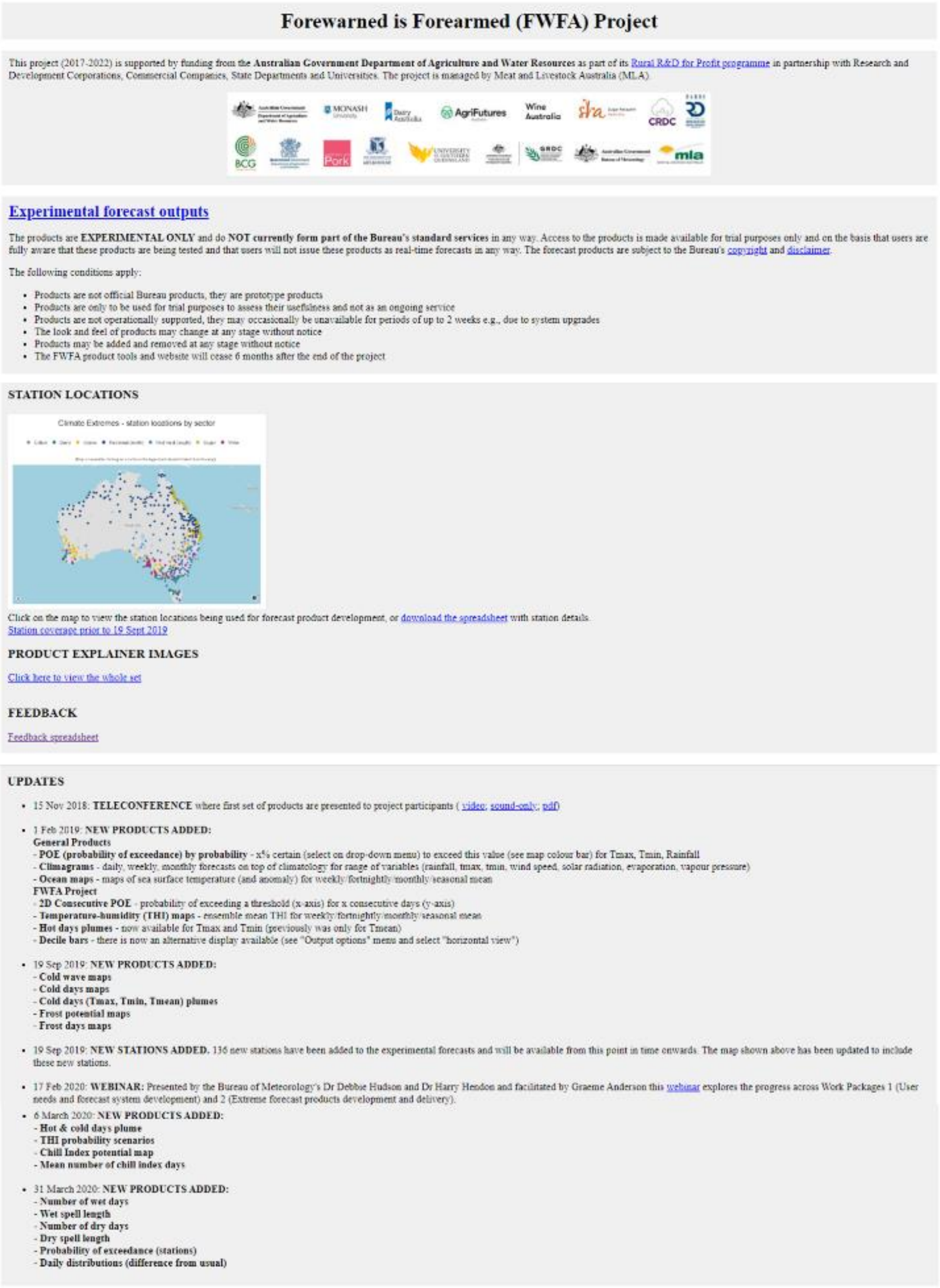


Figure 2: A screenshot of the website hosting the experimental forecast products

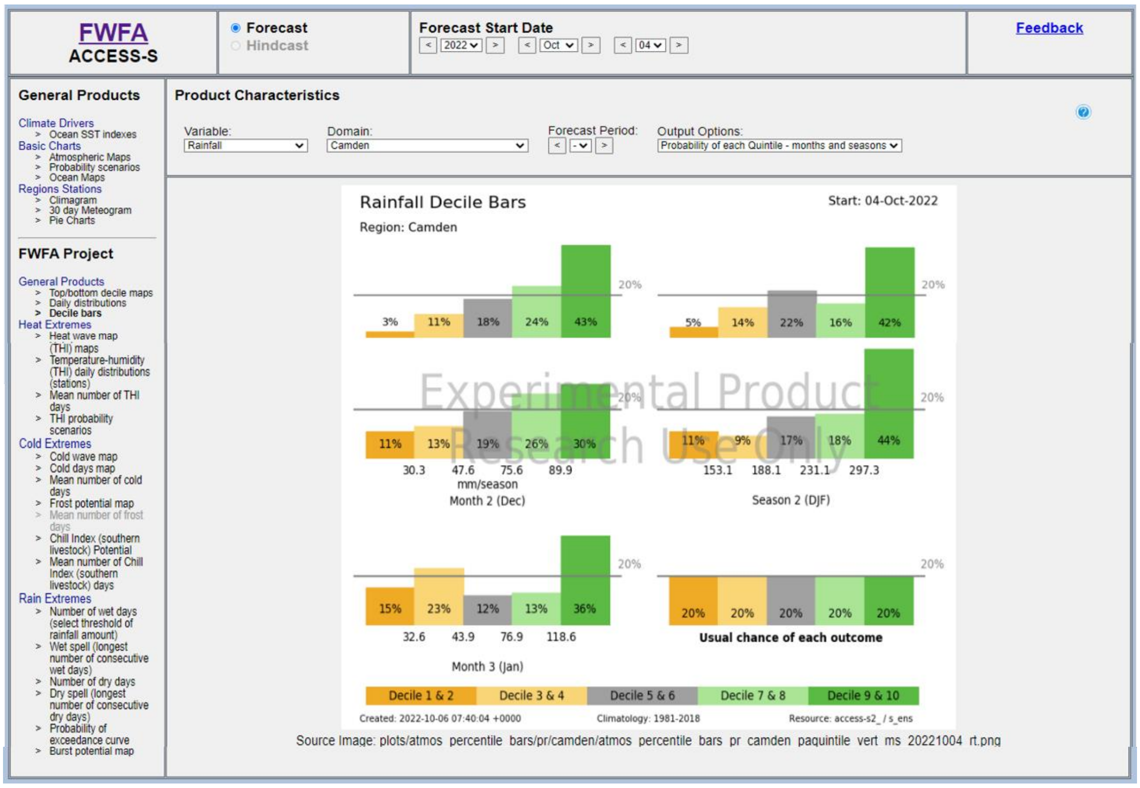


Figure 3: A screenshot of the experimental forecast webpage showing that for any given forecast product there is an accompanying "explainer" (click on the information button)

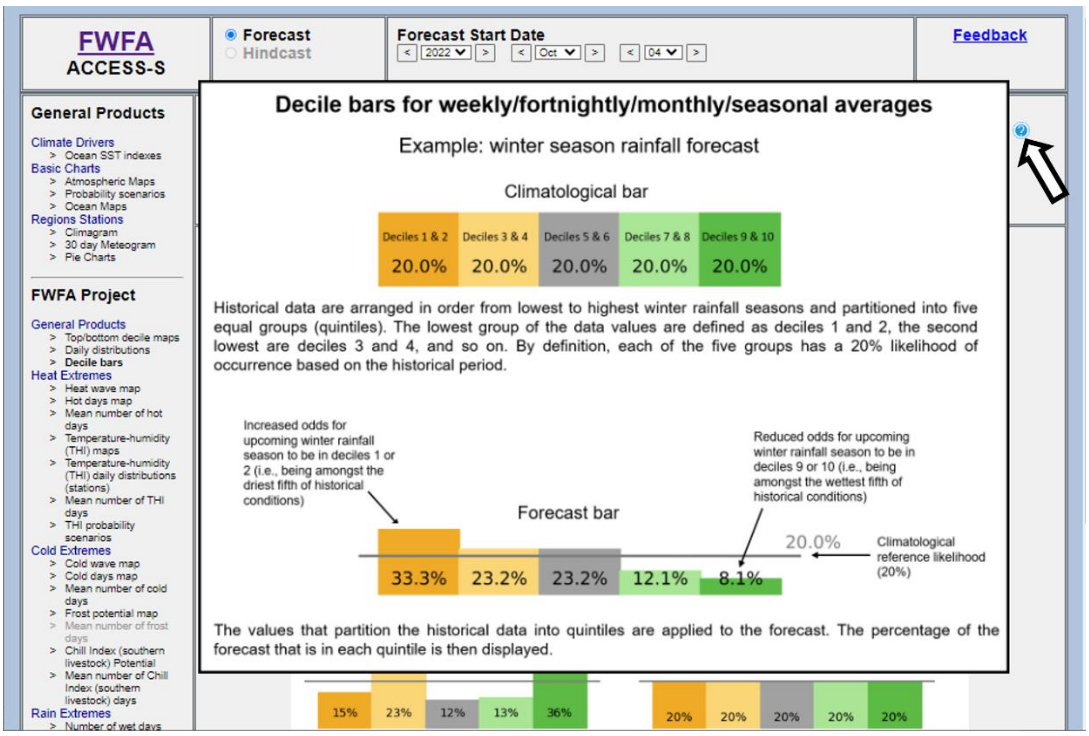
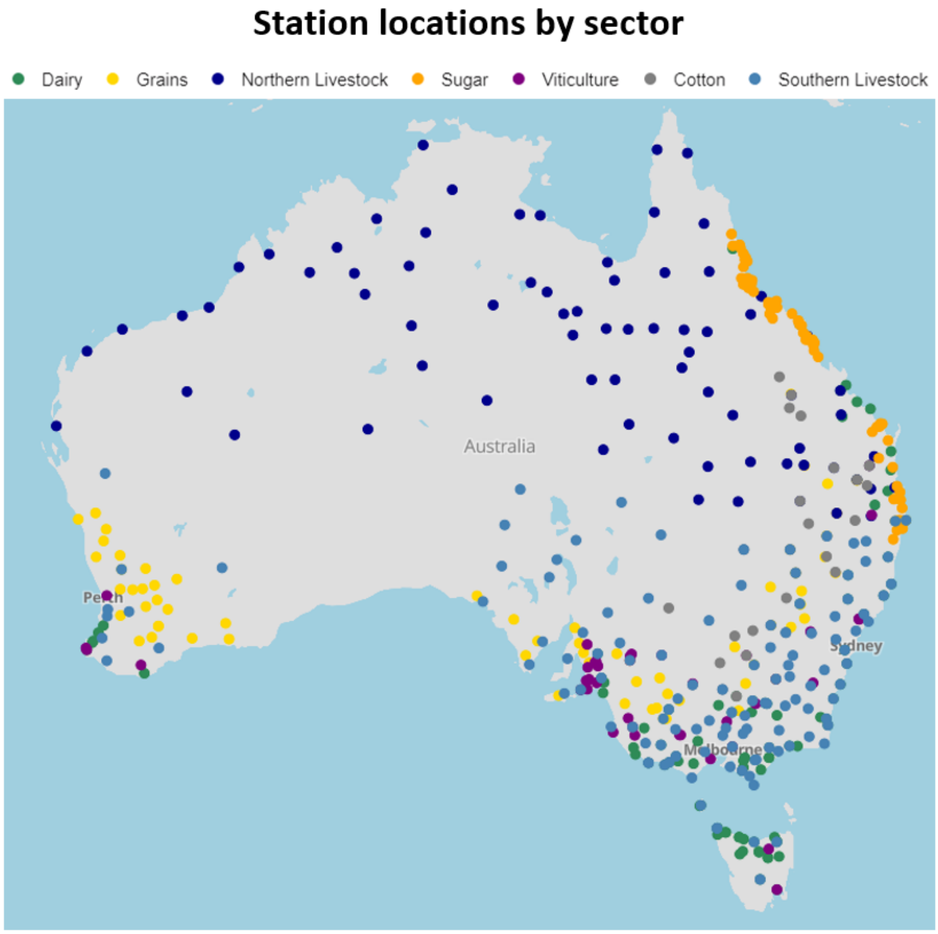


Figure 4. Map showing the set of almost 560 test stations used to trial the location-based products.



Feedback on the experimental products:

The feedback on the experimental products was achieved through various channels, but primarily via direct feedback from project partners, through targeted workshops/webinars with the industry reference groups, as well as webinars coordinated by the FWFA COP.

The feedback was essential to:

- Provide ideas for product development.
- Facilitate the decisions of which forecast products would transition to become official Bureau products.
- Improve the interpretability and understanding of a product, including the required supporting information (particularly if destined to become an official Bureau product).
- Improve the display of the product (particularly if destined to become an official Bureau product).

The feedback on the experimental products was entered into a spreadsheet and responses from the Bureau were provided against each item.

Five experimental products were selected to become official Bureau products:

1. Extremes maps: showing the chance of having very wet, dry, hot or cold conditions.
2. Decile bars for locations: showing the shift in the probabilities compared to usual across five categories for rainfall, maximum and minimum temperatures.
3. Climagrams for locations: timeseries graphs showing the forecast of rainfall totals, maximum and minimum temperatures respectively for the coming weeks and months.
4. Rainfall probability of exceedance curves for locations: graphs showing the probability of exceeding a range of rainfall amounts.
5. Rainfall burst maps: showing the chance of exceeding 3-day rainfall accumulation amounts.

These are described in more detail later.

Insights from the selection of the five operational products:

Selection of the official FWFA products was a project-wide decision, ratified by the project's Industry Advisory Group. From feedback on the experimental products, and in selection of the 5 products, it became clear that:

- There was a desire for *forecast information across all timescales*, with little preference for one timescale overall. Practical decisions are being made at a range of timescales. Users want information across daily, weekly, monthly and seasonal timescales and do not obviously distinguish between "weather" and "climate". This is reflected in all the products, bar the burst-potential maps, being offered for spans covering weeks to seasons.
- There was a strong preference for *location-based products*. Hence, there was significant effort in ensuring that location-based products, used experimentally at specific locations, became available across the entire Australian continent.
- The need for *map-based products* was also recognised, such as the extremes maps and the rainfall burst maps. As one of the Industry Reference Group members commented "Maps are great for an overview, especially for graziers who may be considering other regions for agistment, choosing areas to target for sales, and trying to pick market trends”. Maps also put into context whether local- or regional-scale impacts are likely and can help interpretation of confidence in a forecast (e.g., when located in the middle of a region of the "same colour" compared to when located on the edge). In addition, many managers are working for large companies (e.g., Treasury Wine Estates for viticulture) and dealing with production across large areas of Australia.
- There was a strong desire for visualising the forecast as a *time-series for a given location.* This was clear from the popularity of the climagram product. This enables a clear view of what is coming over the time horizon rather than having to look at multiple maps.
- There was a desire for a *range of complexity* of information and the degree of complexity required was dependant on the user. A comment from the Grains Industry Reference Group was that they may use simpler products for a "quick-look" summary of the forecasts, but that for a business decision they would then want to have as much information as possible, such as shown in the rainfall Probability of Exceedance Curves. Many of the FWFA products are relatively complex and often require some initial explanation. Based on the range of feedback received, the understanding of the products varies considerably.
  The following three comments from Industry Reference Group members provide an indication of some of the range in responses:

- "If the information is presented with too much complexity growers will be turned off."
- "I am fine with the presentation of most products and would not like things 'dumbed down' too much."
- "Now that I am starting to understand how to read the products, I am quite comfortable with the current displays."

Progression of the five products to operations:

Once a product was selected for operations, feedback from internal testing, project partners and Industry Reference Groups informed the refinement of the appearance and interpretation of the selected products. Feedback was sought through webinars, meetings and surveys (e.g., http://piccc.org.au/research/project/FWFA_Forum.html)

Required changes to the front-end (website) were undertaken to host the new products and display them in accordance with agreed visualisation and functionality, including supporting information such as forecast accuracy, period climatology and product explanation.

Code and data used in the experimental version were further developed and optimised to ensure that the operational process ran smoothly and expeditiously across the entire Australian continent for the location-specific products so as not to cause delay. Data not previously presented on the experimental site (such as accuracy and climatology) were prepared and included in the operational process.

Work was done to ensure that the product generation code had been peer reviewed, had suitable unit tests, was thoroughly documented, had an archived code-history and met Bureau computing requirements for deployment into the Bureau production environment.

The code was migrated into the Bureau's production supercomputing environment, while ensuring all data-feeds and transfer processes were robust and maintained the agreed level of service.

The operational forecasts were delivered on the Bureau public webpage, with salient messages about the extremes forecasts from now on included in successive outlook summaries.

Operational products:

The five official Bureau products

The five new forecast products provide producers and advisors with information to improve resilience and productivity and are available on the Bureau's website. Users can select any location to view its chance of unseasonal and extreme temperature and rainfall for the weeks, months, or seasons ahead.

The first two products were released to the public in November 2021 and the final three in June 2022.

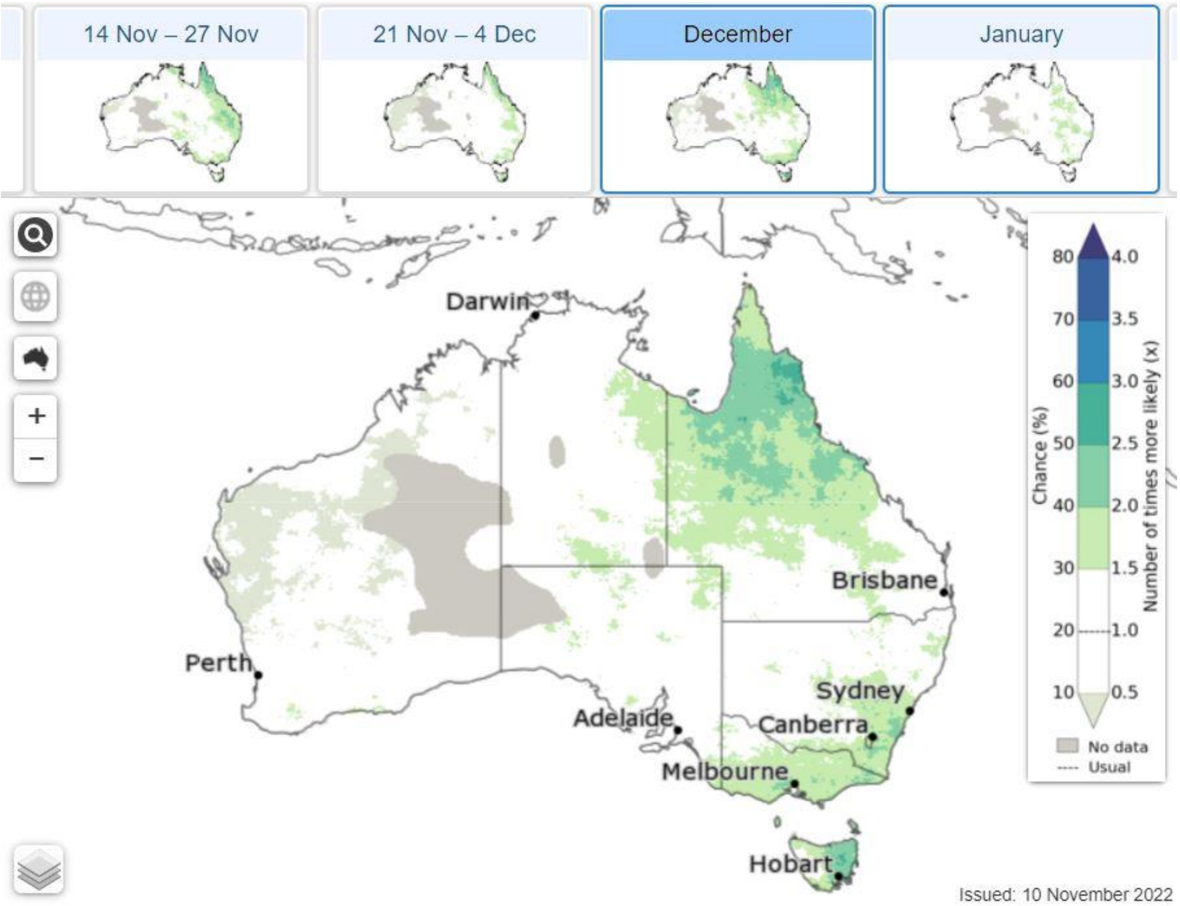
The new forecast products include:

Product 1: Extremes maps

Maps of the chance of having extreme (deciles 1&2 and deciles 9&10 respectively) rainfall, maximum and minimum temperature for the weeks to seasons ahead.

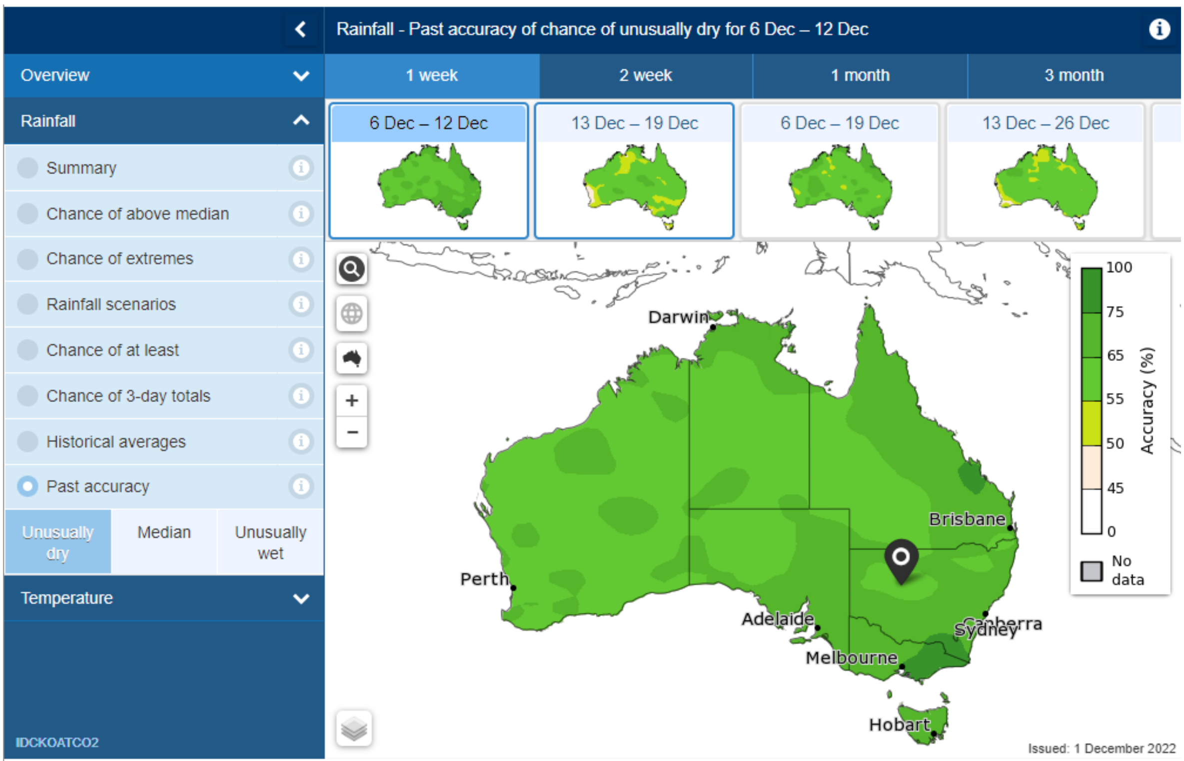
The extremes maps show the chance of having extreme rainfall, extended dry periods, and unusually high or low maximum and minimum temperatures for the weeks, months and seasons ahead (e.g., Fig. 5). These maps are a natural extension of the Bureau's already available probability of above median maps and show the chance of having unusual wet, dry, hot or cold conditions. For these maps "extreme" has been defined as being amongst the driest, wettest, hottest or coldest 20% of periods (weeks/months/seasons) from the climatological (historical) period (i.e., deciles 1 & 2 (bottom 20%) or deciles 9 & 10 (top 20%)).

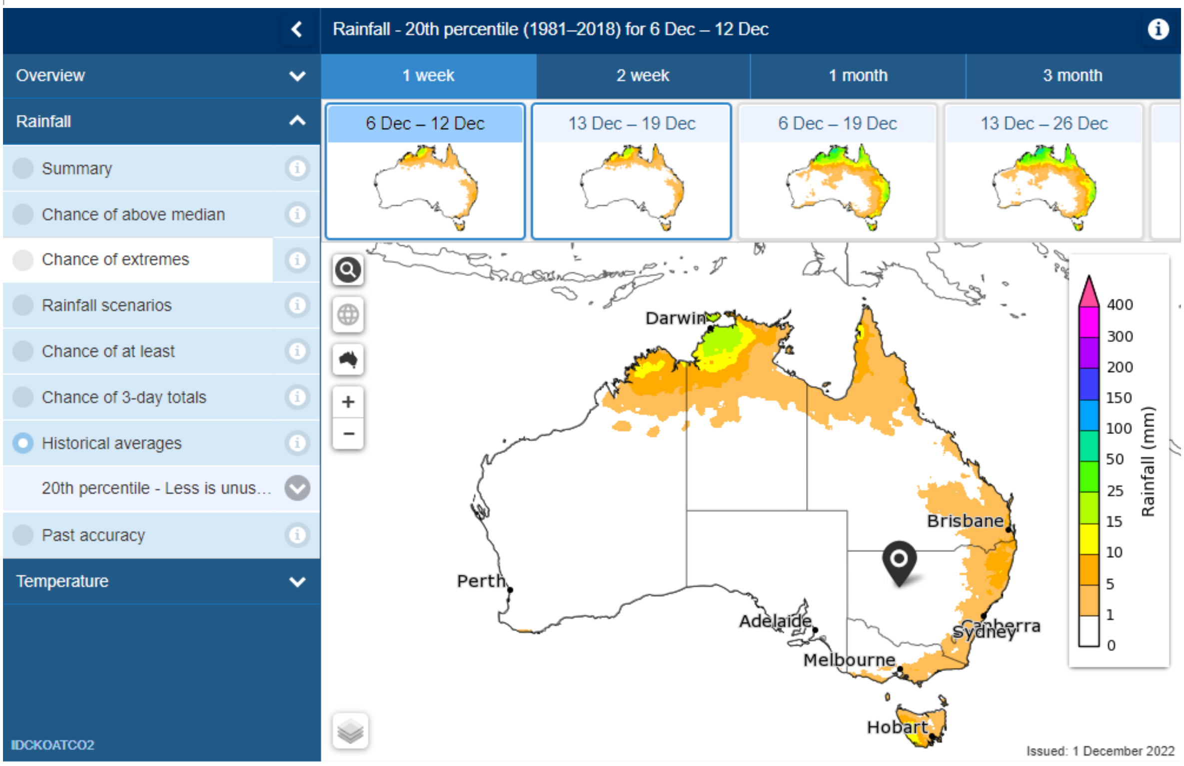
Figure 5: Example of an extreme map: Chance of unusually high rainfall for the next calendar month. This map shows the chance of having rainfall totals in highest 20% of the historical range (decile 9 and 10) in the month of December 2022. Issued 10 November 2022.



The extremes maps are accompanied by maps of forecast skill and the climatological (historical) extreme threshold (i.e., 20th or 80th percentile value) for the particular period under scrutiny are also available from the website (e.g., Figure. 6).

Figure 6: Example of a skill map (top) and a historical threshold map (bottom) for rainfall. The skill map is showing the past accuracy of forecasts of the chance of unusually dry conditions (i.e., being in the bottom 20% of historical conditions) for the week of the 6-12 December. The threshold map is showing the 20th percentile threshold value (calculated over 1981-2018) for the week of the 6-12 December.





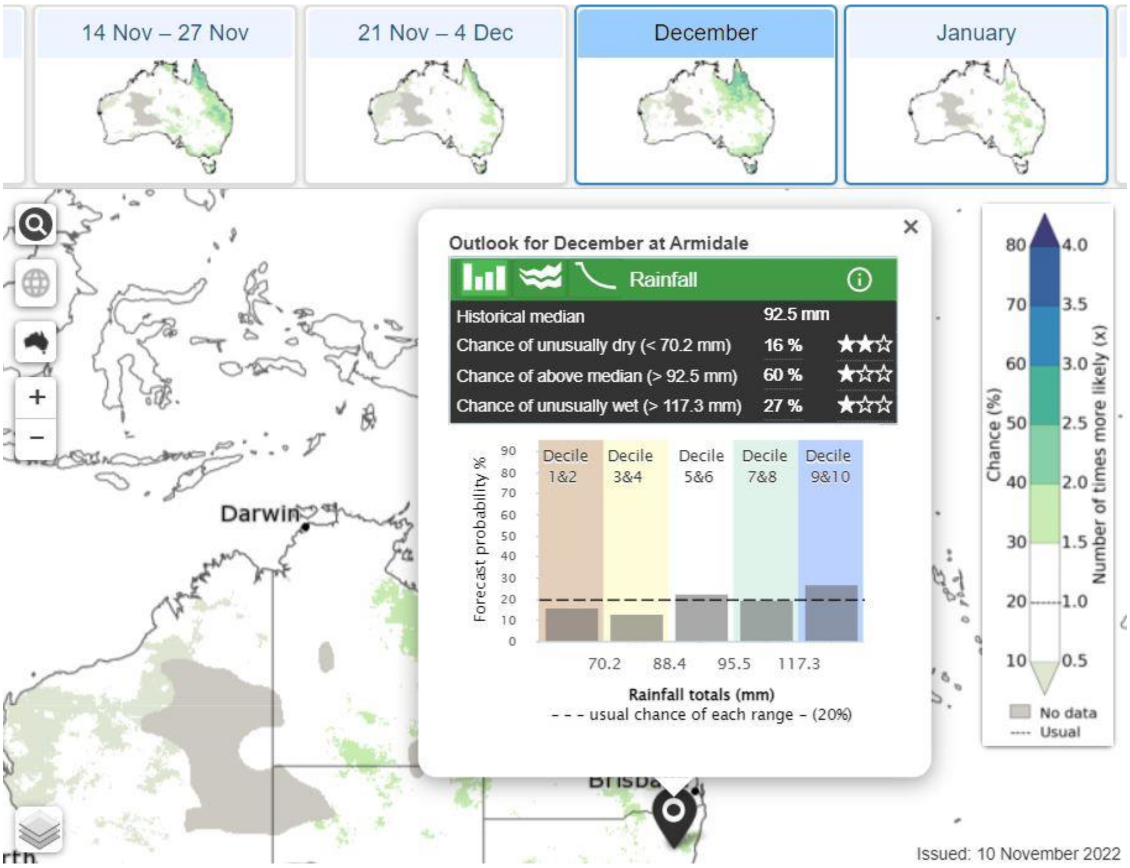
Product 2: Decile Bars

Location-based graphs of the chance of being in any of the climatological quintiles for rainfall and temperature (minimum and maximum) for the weeks to seasons ahead.

The decile (or quintile) bars are location-based bar charts for any location in Australia displaying the likelihood of rain/temperature being in each of 5 climatological ranges (i.e., the likelihood of being in the lowest to the highest 20% of historical records, including and indicate the shift in the probabilities compared to usual across the five categories (quintiles). These are displayed in a pop-up window for a selected location, activated when the location is clicked on, or searched for from an outlook map (e.g., Figure. 7). They are available for rainfall and maximum and minimum temperatures for the weeks, months and seasons ahead. These were one of the most popular products that arose from consultation with producers and advisors, given that they are location-based, show changes relative to what is usually expected across a range of categories and is relatively easy to understand.

An indication of the model skill for each forecast is also included in the display by way of a star-rating (Figure. 7).

Figure 7: Example of the decile bars showing the rainfall forecast for Armidale, NSW for the month of December (generated on 10 November 2022). The forecasts show the probabilities across five different quintile ranges. The long-term average probability ("usual chance") for each category is 20% and the forecasts show the shift in the odds compared to usual.



Product 3: Climagrams

Location-based graphs of the time series of forecast rainfall and temperature (maximum and minimum) for coming weeks and months.

The climagrams are location-based rainfall and temperature time series graphs for any location in Australia. These are weekly and monthly recent observations showing the forecast of rainfall totals, maximum and minimum temperatures respectively for the coming weeks and months (e.g., Figure. 8). They also appear on the pop-up window for a given location. Past observations are also shown on the graph. Insight from producers and advisors really drove the creation of this product due to the strong desire to visualise the forecast as a time-series for a given location (rather than having to look at multiple maps).

An indication of the model skill for each forecast is also included in the display by way of a star-rating (Figure. 8).

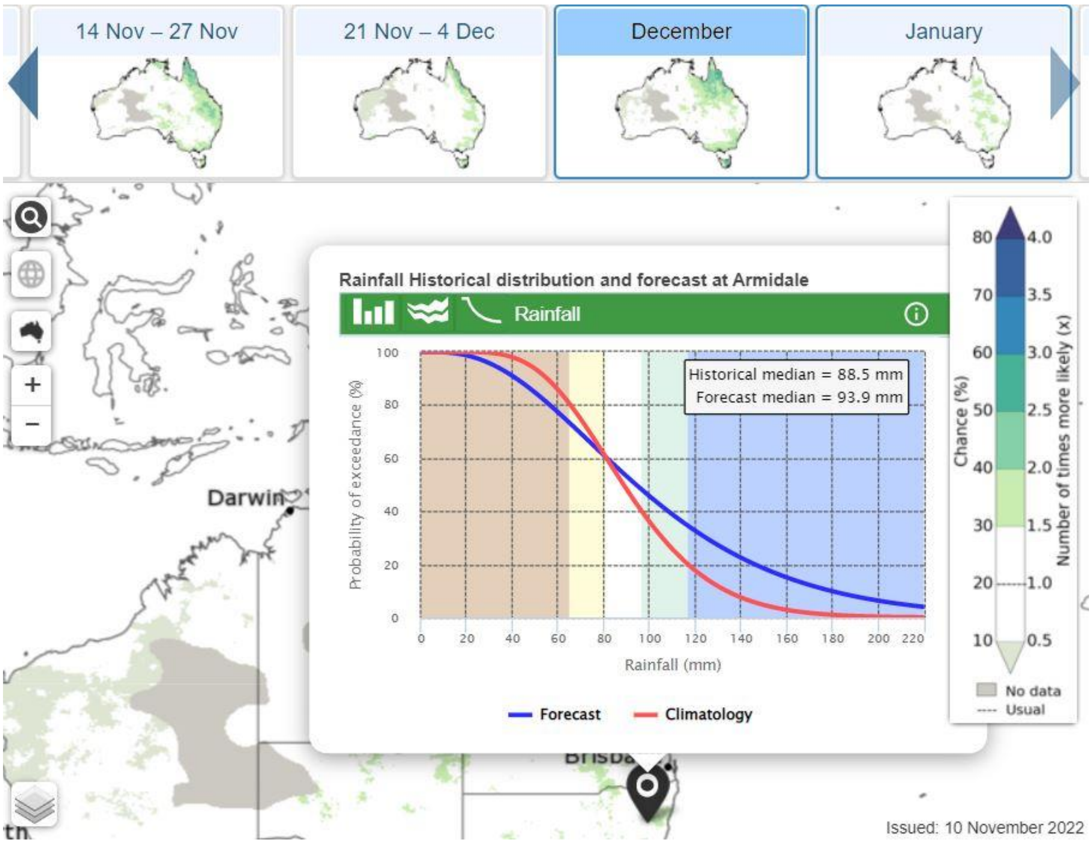
Figure 8: Example of a climagram. The timeseries of observed (solid line) and forecast (box plots) rainfall (y-axis) for consecutive weekly periods (x-axis) for Armidale. The box plots indicate the range in the expected outcomes from the forecasts. The background colour indicates the historical quintile ranges

Product 4: Rainfall Probability of Exceedance

Location-based graphs of the chance of exceeding rainfall totals for weeks to seasons ahead.

The Probability of Exceedance (POE) forecasts are location-based graphs displaying the probability of a comprehensive range of rainfall amounts for the coming weeks to seasons (e.g., Figure. 9). These appear on the pop-up window. They are probably the most complex of the new products. However, once understood, through the consultation process with producers and advisors, the overwhelming feedback was that this product is valuable and will allow users to delve deeper into the forecast information.

Figure 9: Example of a Probability of Exceedance forecast for rainfall, showing the forecast (blue) and usual conditions (red) for Armidale during the month of December 2022. The curves give the probability (y-axis) of experiencing different thresholds of rainfall (x-axis)

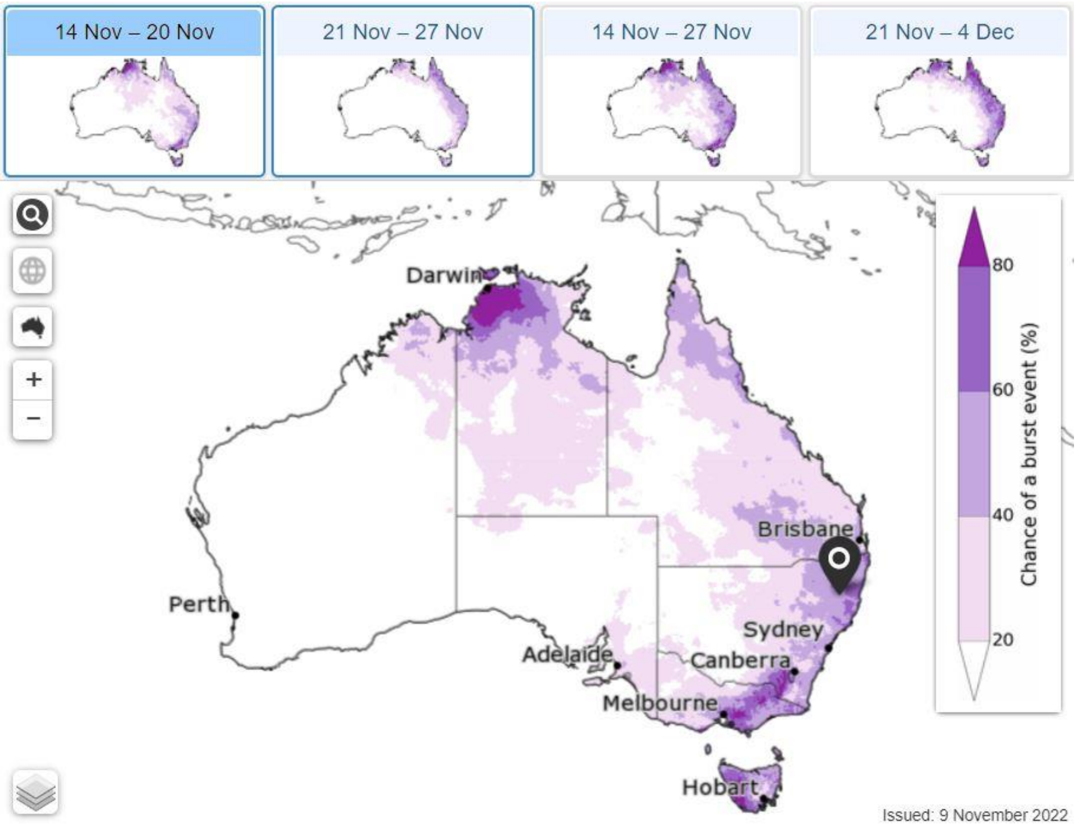


Product 5: 3-day Rainfall Accumulation (or "burst")

Maps of the chance of having specified 3-day rainfall accumulations in the weeks to fortnights ahead.

The three-day rainfall accumulation (or "burst") maps show the chance of having events where three-day rainfall totals ranging from 15mm to 75mm are exceeded in the weeks and fortnights ahead (e.g., Figure. 10). This product provides more information about the distribution of rainfall within a period. For example, there is a big difference in the impact of having a week of light rainfall each day compared to a burst of rainfall over three days. This product was particularly popular with northern producers to, for example, indicate the prospect of achieving "green date" conditions in upcoming weeks.

Figure 10: Example of the 3-day rainfall accumulation (burst) product. The map shows the probability of receiving an intense "burst" of rainfall over a short period of time. This is showing the chance of at least 25 mm within three days during the period 14 November to 20 November 2022. The forecast was issued 9 November.



Additional information accompanying the products:

As part of the website set-up, further information about any of the products is made available via an "info" button, which provides a short summary of the product in a modal window and a link to further detail on another page.

Communications for product release

The Bureau developed a Communications Plan, which was enacted in coordination with broader FWFA activities, to support the release of the new operational features as part of the project delivery.

The Plan included promotional activities that accompanied the initial launch and the release of the remaining products, such as:

- Official statement by Ministers D. Littleproud and S. Ley in November 2021.
- Industry webinars to demonstrate the updated Bureau products.

- A short promotional product video describing the five new products.
- A video providing an overview of the FWFA project and new products.

Project partners were provided with key messages to help them engage with their audiences and promote the value of their investment in the R&D project through the Bureau. This aimed to create awareness and increase the uptake of the new forecasts, particularly among agricultural sector customers and Bureau website users, building confidence and reinforcing the value and impact of the new features in agricultural sector decision making.

In addition, the release of the new forecast products was shared with existing Bureau climate and water outlook subscribers who have an interest climate and water services.

Other and ongoing communication activities:

- Promotional content added to the description for Climate and Water Outlook videos.
- Promotional banner added to the Bureau's climate webpage.
- Training session with approved climate and water spokespeople, communication meteorologists, media team, weather connect and climate data officers.
- Media pitches to industry outlets and publications with case studies.
- Extremes information is now routinely added to the Climate and Water Outlook videos and key messages.

Operational Product Usage:

The FWFA forecast products are a significant enhancement of the climate outlooks service and are available to the public (http://www.bom.gov.au/climate/outlooks). Although the development and delivery were funded by the agriculture sector, the products are not highly tailored and will likely benefit a range of sectors.

Some of the early feedback from the agriculture sector is provided in Appendix 8.5. As well as use by farmers and graziers directly, the FWFA products have played a key role in the recent flood crisis that indirectly has affected many rural communities.

They have been used in a weekly Bureau 'Hazards' slide pack, which has formed the basis of ~100 briefings delivered so far, including to:

- Government – including Minister Watt (Agriculture), Minister Plibersek (Environment), Minister Husic (Science), Assistant Minister McAllister (Climate Change) and Parliamentarians
- Emergency services - NEMA
- Defence
- Water managers - Sydney Water/Water NSW
- National Broadband Network (NBN)
- Australian Energy Market Operator (AEMO)
- Australasian Fire Advisory Council (AFAC)

They are also included in the regular (monthly) Landline ABC-TV climate outlook segments.

In the subsequent three months after launch of the first two products, there were 370,000 visits to the FWFA extremes webpages and maps, with the majority (280,000) viewing rainfall information.

This number constitutes about 8% of the total traffic to the Bureau's climate outlooks website over the same period (4.8 million visits).

Up until late September 2022 there have been nearly one million unique page views of the new extreme event forecast products on the Bureau's website.

4.2 Contribution to program objectives

The objective of the Rural R&D for Profit Program is to realise significant productivity and profitability improvements for primary producers. The FWFA project has significantly contributed to the program objectives in the following three areas (with a focus on the Bureau component).

4.2.1 Generating knowledge, technologies, products or processes that benefit primary producers

Through the project, the Bureau has generated substantial new scientific knowledge (see Appendix 8.1 detailing research papers and reports) which underpins the delivery of a climate extremes service. We have also gained insights into user needs (Shelley, 2018), as well as valuable information on the utility, appearance and interpretation of a wide range of prototype forecast products (see feedback spreadsheet), as well as on the operational forecast products. The feedback came primarily from 6 agricultural industries (sheep, beef, grains, sugar, wine, dairy), although producers in other industries also contributed (e.g., cotton and horticulture).

Five new forecast products are now available on the Bureau's public website, for the benefit of all agriculture. The co-production and collaborative approach with users has ensured that the products are fit-for-purpose and of value for the sector.

Project feedback has indicated that the new forecasts will enable a wide variety of operational and tactical decisions.

For example, managing water purchase and irrigation scheduling, scheduling of planting and harvest, scheduling hazard reduction burning, providing extra shade and water for livestock, moving, selling or buying livestock and biosecurity management.

The Centre for International Economics study (2014) stated that the benefit to agriculture from seasonal forecasting ranges from $958 to $1,930 million per year, without knowledge of extreme events included in their analysis. If actions such as those mentioned above can be taken upon advance warning of an extreme event, a minor (e.g., 5 to 10%) reduction in losses will result in large benefits.

4.2.2 Strengthening pathways to extend the results of rural R&D, including understanding the barriers to adoption

A strong feature of this project has been the direct link between research groups, including the Bureau, and industry-specific reference groups – throughout the project. This allowed producers to provide input to the development and selection of the forecast product – which ultimately increases the success of uptake.

4.2.3 Establishing and fostering industry and research collaborations that form the basis for ongoing innovation and growth of Australian agriculture

The project included collaboration between eight RDCs (GRDC, DA, MLA, RIRDC, SRA, CRDC, WA, APL), research providers, namely the Bureau, Universities (University of Melbourne, University of Southern Queensland, Monash University), state governments (Agriculture Victoria, SARDI, DAF-QLD) and the Birchip Cropping Group (BCG). The project has established successful collaborations between significant government, university, and industry bodies.

4.3 Collaboration

4.3.1 Project partners

Throughout the project there was strong collaboration between the Bureau and the other research providers (University of Melbourne, Monash University, University of Southern Queensland, SARDI, DAF-Q, Agriculture Victoria and the Birchip Cropping Group). This is, for example, evidenced by frequent joint webinars to industry groups, joint participation at Industry Reference Group workshops and joint articles (e.g., Hayman and Hudson 2021; See Appendix 8.1). There were also regular Project Leader Group (PLG) meetings. At the strategic and oversight level, there were regular Industry Advisory Group (IAG) meetings, attended by the General Manager of the Bureau's Agriculture Program and including representation from the investing RDC's. Future projects and extension work will leverage off the relationships and networks that have been established in the FWFA project.

4.3.2 Northern Australia Climate Program (NACP)

There was ongoing collaboration between the FWFA and NACP projects throughout. In particular, the NACP Climate Mates (https://www.nacp.org.au/outreach/climate_mates) provided feedback on the experimental products. In addition, the rainfall burst forecast product (i.e., map of the chance of receiving a particular threshold of rainfall over three consecutive days), which was made operational under FWFA, was developed as part of NACP, but also exposed to FWFA reference groups.

4.3.3 ARC Centre of Excellence for Climate Extremes (CLEX)

We collaborated with CLEX (https://climateextremes.org.au/) − in particular, Andrew King and Todd Lane from University of Melbourne − on the prediction of extreme rainfall and published a joint paper (King et al. 2019: See Appendix 8.1).

4.3.4 International research community (stratospheric processes and impacts)

Research in the FWFA project established that stratospheric warmings above Antarctica can have a significant impact of the likelihood of extremes over Australia. In 2019, after this research had been done, a stratospheric warming event occurred. Our early prediction of the event with ACCESS-S, sparked the convening of a broad coalition of international experts on a daily basis to chart its progression and to discuss its causes and probable impacts. This multi-institution group then wrote a review article led by Dr. Eun-Pa Lim in the Bulletin of the American Meteorological Society (BAMS, see Appendix 8.1). A key feature of the article was our improved capability to predict this event compared to 2002 (the only other time one occurred with similar strength) and our enhanced knowledge of its impacts on surface climate, which primarily arose from our FWFA research.

4.3.5 DCAP Horticulture Project

There was ongoing collaboration between this project and FWFA throughout. In particular, the DCAP project team (https://www.longpaddock.qld.gov.au/dcap/; "DAF#7: The Use of Bureau of Meteorology Multi-Week and Seasonal Forecasts to Facilitate Improved Management Decisions in Queensland's Vegetable Industry") provided feedback and insights on the FWFA experimental products, in particular the pie charts. Some of the early changes that were made to the pie charts came from feedback from the DCAP project team. The pie charts, whilst not in the final 5 chosen to be operational, were the next favoured product.

4.3.6 Climate Services for Agriculture (CSA)

In 2021 the Bureau received funding under the Future Drought Fund for a new program of work: "The Climate Services for Agriculture Program"(https://www.agriculture.gov.au/ag-farm-food/drought/future-drought-fund/climate-services). This work will be delivered in partnership with CSIRO and FarmLink to bring together a variety of climate information specifically for farmers and the agricultural sector. The aim is to help farm businesses anticipate and plan for the impacts of a variable and changing climate. Part of the program included multi-week and seasonal forecasts for agriculture. There were clearly strong links with FWFA, and CSA supported some development of experimental products. There were several discussions where FWFA insights were shared.

4.3.7 Australian Climate Service (ACS)

The Australian Climate Service combines data and expertise from the Bureau, CSIRO, Geoscience Australia, the Australian Bureau of Statistics to provide a step-change in how we collect, share, use and deliver data and information on natural disasters and climate risk now and into the future (https://www.acs.gov.au/). Initially the ACS will supply critical climate hazards information to National Emergency Management Australia (NEMA) to support a national climate resilience framework. The forecast product development and insights from the FWFA project, especially the chance of extremes, are already being fed into the development of this new service. This not only provides strong indications of the positive benefits of the FWFA project, but also highlights that the FWFA products and services may be further supported and expanded into the future, especially those focussed on extremes, creating a wider-ranging product set and greater potential benefits for agriculture than originally anticipated.

4.4 Extension and adoption activities

Extension and adoption activities took place throughout the project, and included:

- Presentations at Industry Reference Groups meetings, Community of Practice sessions and Industry workshops and conferences (Appendix 8.3).
- Input to blogs and media (Appendix 8.3).
- Presentations and papers for the scientific community. Whilst not extension to the agriculture industry, the extension to the scientific community is important for progressing climate science and model development. (Appendices 8.1 and 8.2).

4.5 Lessons learnt and challenges

COVID-19

COVID-19 impacted at least 2–3 years of the project. Most of the Bureau FWFA team was located in Melbourne, which experienced prolonged shutdowns. The COVID-19 situation created challenges associated with:

- Impacts on staff and productivity, for example increased pressures of home-schooling, no or reduced face-to-face meetings (potentially reduced quality of creative interactions) and added stress on staff for a variety of reasons.
- Reduced the opportunity for travel and face-to-face engagement with stakeholders and partners.

However, given the challenges posed by COVID-19, it was impressive that the project adjusted to new ways of working, collaborating and engaging, and all project milestones were still met to a high standard.

Feedback from Industry Reference Groups

A key design feature of the project was direct engagement with users on-the-ground − importantly, having a direct link between researchers and the Industry Reference Groups. There was a reliance on the Industry Reference Groups to provide insights into user-needs for forecasts of extremes, and to provide feedback on the experimental forecast products and the subset of products transitioning to operations.

At times, it was challenging to obtain feedback from the reference groups. This is understandable given:

- The pressures on people's time, particularly when requests (e.g., for participations in workshops, webinars and surveys) come at busy times (such as during harvest).
- COVID restrictions reduced the ability of the project team to travel and meet industry groups.
- Substantial demands on users from a great deal of consultation occurring with the industry.
- A project spanning five years is a long time for sustained user-engagement.

Essentially, Australian agriculture is very busy and the above impacted the extent to which we received feedback on forecast products.

A learning for future projects would be to be mindful of these constraints and to consider additional and novel ways to get feedback more broadly from the industry, particularly when engagement is required over a sustained period. For example, one approach may be to pay users for their involvement in the project.

Communicating probabilities

Communicating probabilistic forecasts remains a challenge, and even more so as products become more complicated as they encompass extremes.

Most users want to know definitively that it will be, for example, wet or dry. However, this is misleading and scientifically not credible given the uncertainties involved. We need to convey the concept of shifts in the odds or likelihoods.

In addition, the heart of risk management is to consider a range of outcomes rather than a single future.

This highlights another challenge: how to apply probabilistic forecasts to decision-making. We have made some headway in communicating probabilities within the FWFA project, but there is still a long way to go. This challenge is recognized internationally (e.g., https://community.wmo.int/meetings/third-wmo-workshop-operational-climate-prediction-ocp-3-20-22-september-2022). It will likely be an ongoing challenge requiring continued and targeted education, extension and improved ways of conveying forecast information.

Communicating forecast skill

Communicating forecast skill or accuracy information is also a key challenge and has been recognised internationally (https://community.wmo.int/meetings/third-wmo-workshop-operational-climate-prediction-ocp-3-20-22-september-2022).

Forecast skill is calculated from the hindcast set i.e., retrospective forecasts over a period in the past (this is standard practice). For ACCESS-S2, the hindcasts span 1981-2018. The reason we use the hindcasts (and not the real-time forecasts) is that we need a sufficiently long period that includes an adequate number of cases of the low frequency influences on Australian climate, like the different phases of ENSO, and for knowing how the skill may vary based on the state of these climate drivers.

The skill information provided with the operational forecasts on the Bureau's website should only be used as a general guide rather than interrogated in detail, because:

- Forecast quality does not necessarily reflect value. Forecast value measures whether a given forecast can be used to inform a decision. For example, forecasts may be extremely accurate over the central Pacific Ocean, but if they are not used to make a decision, then they have little value. The value of a forecast will vary depending on the specific decision and the benefits, costs and losses that are associated with that decision.
- The skill information is the average skill over all the hindcasts for a given time of year. But skill is not static. Skill changes over time and there are windows of forecast opportunity depending on what climate drivers are operating. For example, we know we have more skill under *La Niña* or *El Niño* conditions compared to neutral conditions.
- There is large sampling uncertainty around scores for quantities that are of most interest to the user e.g., regional rainfall. Sampling issues confound getting robust estimates of skill (e.g., limited number of years, limited number of samples) i.e., we have an imperfect knowledge of the skill because our sample is often quite small.
- The years included in hindcast period will influence the skill. We go through periods of higher and lower predictability – there is decadal variability of skill (e.g., imagine a period of years where we have a higher/lower frequency of *La Niña's* e.g., as related to the Interdecadal Pacific Oscillation). Our real-time forecasts could be going through a higher or lower period of predictability compared to the hindcast period.

The above makes understanding how to use the skill information challenging. In addition, with our move towards forecasts of extremes, the skill metrics also become more complex. We cannot use "percent correct" because most of the time we do not forecast extremes and we do not observe extremes.

So, if we used percent correct score it would look excellent! It is a bit like forecasting tornados – if you always say "no tornado is forecast" you'll be correct 99.9% of the time! Instead, we need to use a different metric, called the Relative Operating Characteristics (ROC). The ROC takes into account the hit rate and the false alarm rate when measuring forecast performance.

Provision of skill information to users is vital for multi-week and seasonal forecasting. But, how best to convey and use skill information is an ongoing challenge.

Reliance on ACCESS-S upgrade

The project was reliant on the upgrade of the seasonal forecast system from ACCESS-S1 to ACCESS-S2 during the project. The new FWFA operational products would be based on ACCESS-S2. There were delays with the operational deployment of ACCESS-S2 which impacted some of the FWFA timelines. This was beyond the control of the FWFA project. However, the implications of the delays were appropriately communicated to the project, were mitigated and did not affect the ultimate delivery of project outputs.

<u>The challenge of model development</u>

One component of FWFA was to improve the forecast model. Work on the sea-breeze and convection scheme changes was hampered by computational issues towards the tail-end of the project, which could not be resolved by the project team or by contacts at the Met Office. This component of work would have been greatly assisted through a one-month visit to the Met Office by the Monash research associate employed on the project – as was originally planned. As for many things, COVID-19 disrupted these long-held plans significantly. This slowed down the model development and, in particular, the resolution of the highly technical issue of reproducibility of the new sea-breeze code on different supercomputing processor configurations. One of the challenges of model development work is that it is extremely complex, and many obstacles cannot be anticipated in advance – it is highly exploratory work. However, as mentioned in Section 4.1, the research and development achieved here has subsequently seeded a successful collaboration between the Bureau, Monash University and the UK Met Office Convection Team, such that there are now joint plans and research being done on the inclusion of the sea-breeze scheme into the next version of the Met Office global coupled model.

5 Conclusion

The Forewarned is Forearmed project has used the latest climate science and technology, together with insights from agricultural producers and advisors, to deliver multi-week and seasonal outlooks of extreme weather and climate. The new forecasts are publicly and freely available on the Bureau's climate outlooks website, for the benefit of all agriculture.

The project has encompassed an end-to-end approach − including underpinning science, forecast development, engagement with users, and the delivery and extension of a new service. A strong feature of the project has been the direct link between the research groups and Industry Reference Groups. The benefits of this approach are that it enables efficient feedback between the different components, facilitating a faster and more effective path to delivering practical outcomes to producers.

The value of information lies in its use. Forecasts are only valuable if they provide the information that producers need, if they are issued when producers are making their critical decisions and if they can help inform a decision. The new multi-week and seasonal forecasts have been developed in consultation with several agricultural industries, in particular beef, sheep, dairy, grains, sugar and wine. Engagement with these industries at every step in the project has been central to ultimately realising the benefit of these new forecasts.

Apart from the new forecasts, the project leaves a legacy of:

- Strong networks between researchers from different institutes and agricultural Research and Development Corporations.
- A large set of experimental forecast products.

- A large body of scientific knowledge.
- Key insights into agricultural decision-making and the use of forecast information.

Future research, development and extension should leverage off and build on these established relationships, knowledge and insights to further refine and enhance the quality and interpretability of forecast information available to the agriculture sector.

5.1 Key findings

The new FWFA forecast products, available on the Bureau's outlooks website:

- Were developed in consultation with project partners and agriculture industry reference groups of producers and advisors.
- Meet the needs of feedback collected from all industry groups, thus providing broad utility.
- Use the Bureau's recently updated seasonal forecast model, ACCESS-S2, meaning they are at the cutting edge of global seasonal forecasts.
- Enable users to view the chance of unseasonal and extreme temperature and rainfall for the weeks, months, and seasons ahead.
- Include the following five products:
    1. Extremes maps: showing the chance of having very wet, dry, hot or cold conditions.
    2. Decile bars for locations: showing the shift in the probabilities compared to usual across five categories for rainfall, maximum and minimum temperatures.
    3. Climagrams for locations: timeseries graphs showing the forecast of rainfall totals, maximum and minimum temperatures respectively for the coming weeks and months.
    4. Rainfall probability of exceedance curves for locations: graphs showing the probability of exceeding a range of rainfall amounts.
    5. Rainfall burst maps: showing the chance of exceeding 3-day rainfall accumulation amounts.
- The most popular of the new forecast products across the Industry Reference Groups were the decile bars and the climagrams.
- Include location-based forecasts (available for any location in Australia, defined on a 5km-by-5km grid), given the strong desire from producers for local information.
- Include map-based products, given the recognised value for providing a broader context and for industries that operate across several locations.
- Put the forecast in context of 'usual' conditions.
- Represent a range of complexity of forecast information.
- Include accompanying guidance on forecast skill/accuracy information. The skill for predicting extremes varies strongly by location, season, forecast lead-time and variable. For example, forecasts of temperature are usually more skilful than rainfall.
- Are underpinned by scientific research to understand the predictability and variability of extremes, and the strengths and weaknesses of the ACCESS-S forecast system. This understanding informs the narrative that goes out to users, and the confidence in the forecasts for a given situation. This science is vital for an effective climate service.

5.2 Benefits to industry

The new FWFA forecast products respond to the growing need for information around unseasonal and extreme weather and climate events to build climate resilience and support better-informed decision-making.

Insight gained from Industry Reference Group members and feedback through other channels indicates that the forecast products will be of use for a wide range of operational and tactical agricultural decisions. Examples include, managing irrigation; planting and harvesting times; hay cutting times; pest and disease management; nitrogen top-dressing; paddock management; stock reduction/expansion decisions; managing cattle feed and when to supplement; when to wean calves; when to move to new paddocks or find agistment; when to burn; and timing of field work, machinery hire, travel and staff leave.

The outcomes of the FWFA project will benefit agricultural industries beyond those consulted during the project, as well as other sectors, such as emergency management.

6. Future research and recommendations

The project produced:

- New, publicly available forecasts of extremes for multi-week and seasonal timescales.
- A large set of experimental forecast products.
- A large body of scientific knowledge and development.
- Strong networks between researchers from different institutes and agricultural Research and Development Corporations.
- Key insights into agricultural decision-making and the use of forecast information.

It is strongly recommended that future initiatives draw on these resources, build on the successes of the project, and are cognisant of the learnings, in particular:

1. Co-design and engagement with users in the development of forecast information is crucial for the uptake of forecasts and to deliver practical outcomes.
2. There are a large set of experimental products that were not made official Bureau forecasts. These products will be available to the project until June 2023 to stimulate future business and R&D initiatives.
3. The scope of product development in FWFA was to encompass rainfall, heat and cold extremes. However, during user engagement it was clear that there is also a need for forecasts beyond rainfall and temperature, especially as related to evapotranspiration and wind, and for indices that combine several variables (e.g., a heat load index).
4. FWFA was funded by several agriculture industries. As a result, the FWFA products are of broad utility across the sector. Future work should also address the clear desire for products that are industry-specific and tailored to key decisions.
5. Communicating and quantifying forecast uncertainty is still a challenge and needs to be presented in a way that users can understand. The use of probabilities has long been a barrier in the uptake of seasonal forecasts. New and innovative ways of displaying and communicating forecasts should continue to be explored. In addition, targeted extension and decision-support networks and training should continue to be developed.
6. How to incorporate probabilistic forecasts into decision-making and risk-based frameworks is an ongoing challenge. This needs to be addressed by more research and development on general approaches, as well as one-on-one work with specific industries and for specific decisions.
7. There was a desire for forecasts that extended out to 6-months or longer.
8. Although not focussing on extremes, several users would prefer tercile maps (showing chance of above-average, near-average and below-average conditions) as the first point of entry into the Bureau's climate outlooks website, rather than the "above median" maps (which often result in the misunderstanding that, for example, high probabilities mean high rainfall). In addition, one of the runner-up experimental forecast products in FWFA were the tercile pie charts. They were

very popular with producers, given their simplicity, and could be used in conjunction with tercile maps.

9. There needs to be enhanced understanding of forecast skill information and how best to use it.
10. At times it was challenging to obtaining feedback from the Industry Reference Groups of users. This was completely understandable for the reasons mentioned in Section 4.3. However, for future projects, it would be worth exploring additional and novel ways to obtain feedback more broadly from the industry, particularly when engagement is required over a sustained period.
11. The development of new products and tools should continue to be supported by underpinning science. This is the foundation upon which the products are built. There needs to be ongoing research into understanding climate variability and processes, as well as representation of these processes in the forecast model. Scientific knowledge and understanding is vital for an effective climate service.
12. Forecast quality could be improved by exploring more advanced and different data post-processing and calibration methods, such as machine learning.
13. Ongoing research and development to improve the forecast model is critical to continue to improve forecast skill.
14. Users do not distinguish between weather and climate, and decision-making typically spans a range of timescales - from operational to tactical to strategic – requiring consistent information spanning days to years and longer. This is particularly important for extreme and high-impact events. During the project there was a clear desire for daily time-step forecast information that extends beyond the 7-day weather forecast. To do this there needs to be research on how best to blend forecast information coming from weather forecast models with that coming from seasonal forecast models like ACCESS-S. In addition, novel approaches are required to time-aggregate and display the forecast and associated uncertainties to enable a smooth transition from weather to multi-week timescales. In practice, to be able to distil predictable signals from fundamentally unpredictable noise, longer-range forecasts are usually aggregated in time and have a coarser spatial resolution than weather forecast output.
15. The benefits of end-to-end approach in the project were clear. Spanning foundational science to the delivery of a service allowed for effective interactions at each stage and facilitated valuable cross-pollination of ideas and knowledge between researchers and users.

The following new and in-flight initiatives should seek to benefit from and draw on FWFA outputs:

- Agricultural Innovation Australia (AIA) is funding a new four-year project with the Bureau to improve and enhance seasonal outlook services provided to Australian growers across several industries − Agri-Climate Outlooks (ACO). ACO will draw heavily on the resources and knowledge gained during FWFA and will continue to build on the progress made by FWFA and previous projects. In particular, Workstream 3 of ACO may be a key opportunity to refine and operationalise some of the experimental forecast products developed during FWFA. Workstream 3 aims to develop easy to understand, decision-specific forecast products delivered via appropriate digital channels. In addition, Workstream 2 aims to upskill and train growers and their advisers to interpret and utilise weather, climate and water products to inform agricultural decisions. This workstream will benefit from the training and extension resources developed in FWFA.
- The Climate Services for Agriculture (CSA) program aims to help farmers to adapt to climate variability and change by providing an understanding of the historical, seasonal and future climate at locations. The information will help inform agricultural business decisions. There are several resources and learnings from FWFA that should feed into CSA.
- There was a strong collaboration between FWFA and the Northern Australia Climate Program (NACP). NACP is now progressing into its third phase of funding and will continue to benefit from the networks, knowledge and products from FWFA, but with a focus on northern livestock.

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8. Appendices

8.1 Research papers and published reports

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de Burgh-Day, C. and Dillon, F. 2021. A hybrid parametrisation for precipitation probability of exceedance data. Bureau Research Report No. 052, Bureau of Meteorology Australia

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Hendon, H. H. et al. 2019. Rare forecasted climate event under way in the Southern Hemisphere Nature 573, 495, doi: https://doi.org/10.1038/d41586-019-02858-0

Hendon, H. H., Lim, E.-P., & Abhik, S. 2020. Impact of interannual ozone variations on the downward coupling of the 2002 Southern Hemisphere stratospheric warming. Journal of Geophysical Research: Atmospheres, 125, e2020JD032952. https://doi.org/10.1029/2020JD032952.

King, A. Hudson, D., Lim, E-P, Marshall A.G., Hendon H.H., Lane, T., Alves. O. 2019. Sub-seasonal to seasonal prediction of rainfall extremes in Australia. Quarterly Journal of the Royal Meteorological Society, https://doi.org/10.1002/qj.3789

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Lim, Hudson, Wheeler, et al. 2021b. Why Australia was Not Wet during Spring 2020 despite *La Niña*. Scientific Reports. www.nature.com/articles/s41598-021-97690-w

Lim, E-P., H.H. Hendon and co-authors, 2021c: The 2019 Southern Hemisphere polar stratospheric warming and its impacts. Bulletin of the American Meteorological Society, https://doi.org/10.1175/BAMS-D-20-0112.1

Marshall, A.G., H.H. Hendon, and D. Hudson. 2021. Influence of the Madden-Julian Oscillation on Multiweek Prediction of Australian Rainfall Extremes using the ACCESS-S1 Prediction System. J. Southern Hem. Earth Sys. Sci., https://doi.org/10.1071/ES21001

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Wang, G. and Hendon, H.H. 2020. Impacts of the Madden–Julian Oscillation on wintertime Australian minimum temperatures and Southern Hemisphere circulation. Climate Dynamics, https://doi.org/10.1007/s00382-020-05432-x.

8.2 Conference presentations

Hudson, D. 2018 'Forewarned is Forearmed: equipping farmers and agricultural value chains to proactively manage the impacts of extreme climate events', Joint 25th AMOS (Australian Meteorological and Oceanographic Society) Conference and 12th International Conference for Southern Hemisphere Meteorology and Oceanography (7 February).

Lim, E. 2018 'Impact of initial land surface conditions on predictive skill of Australian daily maximum temperature', Joint 25th AMOS (Australian Meteorological and Oceanographic Society) Conference and 12th International Conference for Southern Hemisphere Meteorology and Oceanography (6 February).

Hudson, D. 2018. 'Moving from concept to climate service: how we can meet the needs of a climate smart community', Keynote presentation at Second International Conference on Subseasonal to Seasonal Prediction (17-21 September, Colorado, USA).

Lim, E-P. 2018. 'Impacts and Predictability of Southern Hemisphere Stratosphere-Troposphere Coupling'. SPARC (Stratosphere-troposphere Processes And their Role in Climate) General Assembly, (1-5 October, Japan).

Hudson, D. 2018. BoM presentation on skill / confidence levels in BoM forecasts and an overview of ACCESS S and multi week products in development. Southern Region Agronomists Workshop, 1 November 2018 Adelaide)

Hudson, D. 2018. 'Ensemble forecast products for user decisions on multi-week to seasonal timescales'. Bureau of Meteorology Annual R&D Workshop (26-30 November, Melbourne)

Hendon, H.H. 2019. 'MJO Impact on Temperature Extremes over Australia during Austral Spring'. Workshop on Predictability, dynamics and applications research using the TIGGE and S2S ensembles (2-5 April, ECMWF, Reading UK)

Hudson, D. 2019. 'Forewarned is Forearmed – Managing the impacts of extreme climate events', Ag Excellence Forum. (5 April, Adelaide).

de Burgh-Day, C. 2019. 'Forecasting extremes to aid agricultural decisions on multi-week to seasonal timescales', AMOS-ICTMO conference (11-14 June, Darwin)

Hendon, H.H. 2019. 'MJO impact on temperature extremes over Australia during Austral Spring', AMOS-ICTMO conference (11-14 June, Darwin)

Lim E-P. 2019. 'Impact of Southern Hemisphere Stratospheric Polar Vortex Weakening on Australian Climate Extremes' (poster), AMOS-ICTMO conference (11-14 June, Darwin)

Wang, G. 2019. 'Impact of MJO on Temperature Extremes over Australia during Austral Spring', UK Met Office Global Coupled Modelling Teleconnections Workshop (26 June, Exeter, UK)

Hendon, H.H. 2019. Teleconnection from the Southern Hemisphere Polar Vortex to Australian surface climate extremes', UK Met Office Global Coupled Modelling Teleconnections Workshop (26 June, Exeter, UK; Hendon-video remote)

de Burgh-Day, C. 2019. 'How our seasonal forecasting is getting better'. Australian Wine Industry Technical Conference: Workshop on NextGen weather and climate information for your wine region. (21 July, Adelaide)

Lim, E.-P. 2019. 'The sudden warming of the austral polar vortex in 2019'. A Joint DynVarMIP -SPARC DynVar - SNAP Meeting. (23 October, Marid, Spain)

Yorgun, S. 2019. 'An Evaluation of ACCESS-S1 in Simulating Hot Summers over Australia', ARC COE for Climate Extremes (CLEX) Annual Workshop. (20 November, Hobart)

Lim, E.-P. 2019. 'Stratospheric Polar Vortex Weakening and its Impact on Australian Climate Extremes'. ARC COE for Climate Extremes (CLEX) Annual Workshop. (22 November, Hobart)

Wang, G. 2019 'Impacts and Predictability of Australian Wintertime Minimum Temperatures Driven by the MJO'. Bureau Annual R&D Workshop. (27 November, Melbourne)

Lim, E-P. 2019. 'Seasonal prediction of SH stratospheric polar vortex weakening and its impact on Australian climate'. Bureau Annual R&D Workshop (27 November, Melbourne)

Hendon, H.H. 2020. 'Impact of Ozone Variation on Predicting Downward Coupling from the Southern Hemisphere Polar Stratospheric Vortex: A Case Study for the 2002 Sudden Stratospheric Warming'. AMOS (Australian Meteorological and Oceanographic Society) Conference. (12 February, Fremantle)

Lim, E.-P. 2020.' Significant weakening of the stratospheric polar vortex over Antarctica in spring 2019'. AMOS (Australian Meteorological and Oceanographic Society) Conference. (12 February Fremantle)

Yorgun, S. 2020. 'An Evaluation of ACCESS-S1 in Simulating Hot Summers over Australia'. AMOS (Australian Meteorological and Oceanographic Society) Conference. (12 February Fremantle)

de Burgh-Day, C. 2020. 'Forecasting climate extremes to aid decisions on multi-week timescales'. EGU (European Geophysical Union) General Assembly, (4–8 May, Online).

de Burgh-Day, C. 2020. Forecasting climate extremes to aid decisions on multi-week timescales, WMO S2S Prediction Project Webinar Series, (29 July, Online)

Hendon, H.H. 2021. 'Long lead prediction of the 2019 climate extremes'. AMOS (Australian Meteorological and Oceanographic Society) conference (9 February)

Hudson, D. 2021. 'Forecasts for agricultural decision-making on multi-week to seasonal timescales'. CRSPI online forum (30 March)

Hudson, D. 2021. 'Forecasts for agricultural decision-making on sub-seasonal to seasonal timescales: a user-centred approach'. AGU (American Geophysical Union) Fall Conference (16 Dec, Online).

Marshall, A. 2022. 'MJO impacts on Australian climate extremes'. ICSHMO (International Conference on Southern Hemisphere Meteorology and Oceanography) conference, (February)

Ramchurn, A. and Wang, W. 2022. 'Delivering extreme climate outlooks - Forewarned is Forearmed'. AMOS (Australian Meteorological and Oceanographic Society) Conference (28 Nov-2 Dec, Adelaide).

8.3 Media, FWFA COP presentations and popular articles

The **release of the new forecast products** on the Bureau website was accompanied by a comprehensive communications plan and several Bureau promotion activities, including:

- Joint media release issued by the Minster for the Environment (Minister Ley) and Minister for Agriculture and Northern Australia (Minister Littleproud) upon release of the first two operational products.
- Banners and 'calls to action' on Bureau climate pages promoting the new climate extremes products (see below).
- Bureau social media posts, including a Bureau YouTube video summarising the FWFA products.
- Bureau involvement in a video providing an overview of the FWFA project and new products.
- Inclusion of the new products in the Bureau's monthly video which appears on Landline (ABC-TV).
- A direct email out to current subscribers to the climate outlooks alerting them to the new FWFA products (approximately 11,000 subscribers).
- Internal product Q&A to assist BoM staff understand and communicate the FWFA new products.
- A set of Key Messages to be used when talking about the new products to Bureau customers

There were several comms activities around the project work on the **sudden stratospheric warming research and its impact on extremes**. This is a positive outcome for the project, underscoring the benefits of the underpinning research, which leads to understanding and confidence in the forecasts:

- ABC news
- ABC radio
- UK Met Office podcast
- The Conversation Article

Other media:

- Farm Weekly article
- Farm Online article
- Rural Queensland Today
- ABC Weather article
- Agriculture Victoria podcast

FWFA COP webinars:

- Hudson, D. (November 2018). Presentation introducing the new experimental products to the COP and reference groups.
- Wang, G. (August 2019) Madden-Julian Oscillation (MJO): How does it affect heat extremes & what predictive skill does ACCESS have?

- Lim, E-P., (October 2019). Impact of Southern Hemisphere Stratospheric Polar Vortex weakening on Australian day-time temperature extremes in spring-summer.
- Hudson, D. (October 2019). Update on FWFA experimental forecasts, including new "cold extremes" products.
- Hudson, D. (August 2020). Update on FWFA experimental forecasts, including new "rainfall extremes" products.
- Hudson, D. (April 2021). FWFA Products 4 & 5.
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FWFA webinars hosted by University of Melbourne:
https://piccc.org.au/research/project/FWFA.html

- Hendon, H., Hudson, D., Hendon, H. (February 2020). 1) User needs and forecast development and 2) extreme forecasts development and delivery.
- Watkins, A., Ramchurn, A. (November 2021). Presentation of operational products 1 and 2.
- Watkins, A., Ramchurn, A. (July 2022). Presentation of operational products 3, 4 and 5.

Other:

Andrew Watkins, Harry Hendon, Andrew Marshall and/or Matthew Wheeler provided monthly climate briefings on the current state of the climate and upcoming conditions (note, this was separate from the FWFA COP seminar series).

There were several Bureau presentations at Industry Reference Group meetings.

Bureau staff provided input to several Climate Kelpie Blogs – an important communication channel for the project.

8.4 Experimental products

Table 1 shows a list of the experimental forecast products developed during the project for heat, cold and rainfall extremes. These forecast products were updated in real-time and available to project partners, stakeholders and Industry Reference Groups.

Table A1: Experimental forecast products developed during the project for heat, cold and rainfall extremes.

Product	Variable	Lead time	Description
General (heat, cold and rainfall)			
Top/bottom quintile (maps)	Maximum temperature (Tmax), Minimum temperature (Tmin), Rainfall	Weeks to seasons ahead	Maps of the probability of being in the top/bottom quintile for Tmax/Tmin/rainfall for a given lead time.
Climagrams (stations)	Tmax, Tmin, Rainfall	Daily, weekly and monthly	Box-plot timeseries of upcoming days, weeks, or months showing the range of possible outcomes.
Decile/quintile bars (stations)	Tmax, Tmin, Rainfall	Weeks to seasons ahead	Bars showing the forecast probability for each of the 5 (quintile) categories (i.e., the categories include the following deciles: 1+2, 3+4, 5+6, 7+8, 9+10). The climatological expected probability in each category is 20%. The forecast product shows where there is a reduced/increased likelihood for a given category.
Pie charts (stations)	Tmax, Tmin, Rainfall	Weeks to seasons ahead	Three-category pie charts showing the probability for each tercile (e.g. showing probability of being drier, near-normal or wetter than usual. Similarly, for Tmax and Tmin).
Daily distributions (stations)	Tmax, Tmin, Rainfall	Weeks to seasons ahead	The forecast shows the distribution of daily (number of days) of various Tmax/Tmin/rainfall totals from the forecast for a given period. The product also shows what is normally expected at the given time of year (climatology), thus highlighting any shifts compared to climatology.
Heat Extremes			
Heatwave maps	A heatwave is defined as 3 or more consecutive days exceeding the 90th percentile of daily mean temperature.	Weeks to fortnights ahead	Maps of the probability of having a warmwave/heatwave in a given period. (Note: the heatwave is defined using a seasonally varying threshold – this will, for example, pick up warm waves in the winter half of the year)
Hot days probability maps	Daily Tmax above the 90th percentile of daily Tmax.	Weeks to seasons ahead	Chance of having more than the usual number of hot days (or nights) in a given period. (Note: a hot day is defined using a seasonally varying threshold – this will, for example, pick up hot days in the winter half of the year)

	Also available for daily Tmin and Tmean		
Number of hot days	As above	Weeks to seasons ahead	Number of hot days (or nights) in the period (from the ensemble mean). The days do not need to be consecutive.
Hot days plume (stations)	Daily Tmean	Daily out to 30 days	This product shows the daily forecast plume of Tmax out to 30 days. The plume shows the spread (10th, 25th, median, 75th, 90th percentiles of the forecast ensemble) of the forecast ensemble members and highlights (in orange) when the forecast exceeds the climatological (long-term) 90th percentile.
Temperature-humidity maps	Daily Tmax (T_max), 9am vapour pressure (VP_9am) and 3pm vapour pressure (VP_3pm).	Weeks to seasons ahead	Maps showing the THI expected (ensemble mean). The temperature-humidity index (THI) is of general interest to livestock industries and is used for warnings in the Dairy Industry. THI = T_max + 0.36 * T_d + 41.2 • T_d is the daily dew point temperature • T_d = (234.5 * ln(VP / 6.112)) / (17.67 - ln(VP / 6.112)) VP is the mean of the 9am and 3pm VP
Temperature-humidity distributions (stations)	As above .	Weeks to seasons ahead	The forecast product will allow users to identify specific THI thresholds of interest (e.g., when THI>78, milk production is seriously affected). The forecast shows the distribution of daily THI data from the forecast for a given period. The forecast product also allows the user to compare the forecast with what is normally expected for the daily distribution of THI at the given time of year (climatology), thus highlighting if there are any shifts compared to climatology. THI is defined as above.
Temperature-humidity probability of exceedance scenarios	As above	Weeks to seasons ahead	The average THI over the period that has a 25% (or 50% or 75%) chance of occurring. THI is defined as above.
Mean number of THI days	As above	Weeks to seasons ahead	Maps show the expected number (ensemble mean) of mild, moderate, high or severe THI days in the forecast period: Moderate (>72), high (>78), severe (>82) THI is defined as above.
Cold extremes			
Coldwave maps	A coldwave is defined as 3 or more consecutive days less than the 10th	Weeks to fortnights ahead	Maps of the probability of having a cool/coldwave in a given period. (Note: the coldwave is defined using a seasonally varying threshold – this will, for example, pick up "cool waves" in the summer half of the year)

	percentile of daily mean temperature.		
Cold days probability maps	Daily Tmax below the 10^{th} percentile of daily Tmax. Also available for daily Tmin and Tmean	Weeks to seasons ahead	Chance of having more than the usual number of cold days (or nights) in a given period. (Note: a cold day is defined using a seasonally varying threshold – this will, for example, pick up cold days in the summer half of the year)
Number of cold days	As above	Weeks to seasons ahead	Number of cold days (or nights) in the period (from the ensemble mean). The days do not need to be consecutive.
Cold days plume (stations)	Available for daily Tmean, Tmin, Tmax	Daily out to 30 days	This product shows the daily forecast plume of Tmax, Tmin or Tmean out to 30 days. The plume shows the spread (10^{th}, 25^{th}, median, 75^{th}, 90^{th} percentiles of the forecast ensemble) of the forecast ensemble members and highlights (in blue) when the forecast is less than the climatological observed 10^{th} percentile.
Frost potential maps	Daily Tmin	Weeks to fortnights ahead	Chance of having at least one frost in the forecast period. The forecast is based on the minimum temperature being below a given threshold (<2deg; <0deg; <-2deg; or <-5deg). These thresholds have been chosen to indicate days when the temperature may be suitable for frost formation. It is called "frost potential" because frost may or may not form on these days, depending on other factors, such as wind, local topography and humidity
Number of frost days	Daily Tmin	Weeks to seasons ahead	Expected number of frosts in the forecast period (ensemble mean). The forecast is based on the minimum temperature being below a given threshold. The thresholds are defined as noted above.
Chill Index Potential (southern livestock)	Daily mean temperature, rainfall and wind speed	Weeks to fortnights ahead	Maps showing the chance of having at least one mild/moderate/high/severe Chill Index day in the forecast period. Chill Index (Carter et al. 2019) is defined as the potential heat loss in kJ/m2/hr, and is given by: C = (11.7 + 3.1v0.5) (40-T) + 418(1-e-0.04x) + 481 • v is the mean daily wind velocity (m/sec), • T is the average daily temperature (degC) • x is the daily rainfall (mm). The forecast is based on the Chill Index being above a given threshold. Here we are plotting the probability of at least one day of mild, moderate, high or severe Chill Index from the range of outcomes, where: Mild (> 900), moderate (> 1000), high (> 1100), severe (> 1200)
Mean number of Chill Index	Daily mean temperature,	Weeks to seasons ahead	Maps show the expected number (ensemble mean) of mild, moderate, high or severe Chill Index days in the forecast period.

days (southern livestock)	rainfall and wind speed		Chill index is defined as above.
Rainfall Extremes			
Number of wet days (select threshold of rainfall amount)	Daily rainfall totals	Weeks to seasons ahead	Maps of the number of "wet days" in the forecast period (ensemble mean), where what is counted as "wet" can be selected from a drop down menu (i.e. daily rainfall >0.2mm, >5mm, >10mm, >15mm, >25mm or >50mm).
Longest wet spell (number of consecutive wet days)	Daily rainfall totals	Weeks to seasons ahead	Maps showing the length of the longest wet spell in the period, where a wet day is >0.2 mm of rain. Here we are using the *median* of the longest wet spell from the range of outcomes.
Number of dry days	Daily rainfall totals	Weeks to seasons ahead	Maps of the number of "dry days" in the forecast period, where a dry day is <0.2 mm of rain Here we are using the *median* number of dry days from the range of outcomes.
Longest dry spell (number of consecutive dry days)	Daily rainfall totals	Weeks to seasons ahead	Maps showing the length of the longest dry spell in the period, where a dry day is <0.2 mm of rain. Here we are using the *median* of the longest wet spell from the range of outcomes.
Probability of exceedance curves for stations	Rainfall totals over a period	Weeks to seasons ahead	Probability of exceedance (POE) curves for rainfall totals in a given period. Curves for the forecast POE (black) and the usual POE (i.e., climatology; grey) are shown. The rainfall threshold is shown on the x-axis, and the associated probability of exceeding that threshold on the y-axis.
Rainfall burst (3-day accumulations)	3-day rainfall accumulations	Weeks to fortnights ahead	Maps showing the chance of exceeding 3-day rainfall totals, ranging from 15 mm to 75 mm.

8.5 Examples of feedback on the operational products

Some examples of feedback from the Agriculture Sector on the new operational forecast products are as follows:

- "Whilst weather forecasting is not an exact science, these tools will be really valuable in planning our work program on a seasonal level." - Dairy Farmer.
- "These new products give a fuller picture to the seasonal outlook and answer some common questions posed by farmers. Grain farmers point out that it is easy to manage seasons that are slightly above or slightly below the average; they are interested in the very wet or dry and very warm or cool seasons." - SARDI crop researcher.
- "They are valuable products. Being forewarned we can change things around in our system according to what these products are forecasting." - Sugar Cane grower.
- "These maps are better than the current probability above or below median because a farmer wants to know the probability of the drier/ wetter/hotter/cooler and therefore the deciles at the extremes are of more interest." - Beef producer.
- "It has been very insightful being a part of this project. To pin down what could be of value in on farm decision making has been challenging. The process of working with the BoM on these FWFA products highlights the value of a co-design approach in delivering a useful outcome." - Dairy Farmer.
- "Farmers over the last 15 years have always expressed their frustration of the limitations of a plus and minus median forecast. It is with great joy that will now be able to ascertain how dry, how wet, how hot, how cold, couched in terms of probability of course!" Agriculture Victoria Agronomist.
- "I'm excited about the new seasonal outlook model that incorporates research from the Forewarned is forearmed project. I think for famers across Australia the ability to see the extremes of very hot, cold or wet and dry with a good idea of accuracy will help with decision making. We will definitely use these products in planning for timing of stock purchases and sales and timing of pasture renovations. The current wet outlook for the next three months gives us confidence with our stock selling program, as rain predicted in the north will continue to underpin strong cattle store market." - Sheep farmer.
- "We like to use the Forewarned is Forearmed (FWFA) Decile Bar Tool….. I find them very clear and easy to see, you can find your location on the map and hover your mouse over it and it will take you to the nearest weather station and give you the probabilities you need to help make decisions on farm….. We use the FWFA decile bar tool for making decisions about seasonal stocking rates and predicting pasture feed growth and availability, so we can match our stocking rate to the carrying capacity. When we are trying to decide how many stock we can run over summer and winter, climate is very important and as we don't really buy in feed, we prefer to use the pasture we grow on farm. The decile bar tool allows us to decide whether or not we are going to sell or hold stock and if it's to sell, it means that we can make this decision early, ahead of the market." (Livestock Producer. Taken from: https://www.climatekelpie.com.au/index.php/2022/06/24/new-decile-bar-tool-a-winner-for-producers/).
- "Based on the science now and the information from these new tools, I probably won't plant summer legumes. I'll wait until March next year and then plant winter legumes because they

can stand up to a lot more water at that time," (Sugar Cane grower. Taken from: https://www.climatekelpie.com.au/index.php/2021/12/15/forecasting-extreme-climate-events-new-tools-help-growers-to-prepare/).

- "As a producer. It's been great, the chance to use the developmental products for extended periods has been a real bonus to see first-hand what the Access S program was capable of in the longer term forecast area. The interaction with the FWFA project members has always been excellent in terms of them providing the background information required to understand what the project could deliver. I always felt feedback was something genuinely sort and valued. The professionalism and commitment of FWFA project members to develop relevant and accessible products that would improve longer range forecasts has been a standout feature of the project team" - Dairy Farmer.

8.6 Intellectual property (IP)

The following Bureau IP was generated during the project:

- Retrospective and real-time experimental extremes forecast products (graphical and data). The graphical experimental products, available on the research website (http://poama.bom.gov.au/project/fwfa/index.html), will be available to project partners until 30 June 2023, to enable planning for future initiatives.
- Operational extremes products and accompanying information (graphical and data). The forecast products are fully operational at Bureau. They are part of the Bureau's official set of products and displayed on the Bureau public website.
- Reports published in the Bureau Research Report Series (http://www.bom.gov.au/research/research-reports.shtml
- Bureau promotional material.