

Final report

Northern Australia Climate Program 3

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Abstract

The Northern Australia Climate Program Phase 3 (NACP3) was undertaken to improve how red meat producers in northern Australia use climate and weather information to manage drought and climate risk. Adoption of existing forecasts had been limited due to variable accuracy, low relevance to farm decisions, and lack of confidence in using the information. The project aimed to improve forecast capability, develop practical decision-support tools and provide direct support to red meat producers.

The project was delivered through an integrated approach combining research, product development and extension. Research improved the underlying prediction model, understanding of climate drivers and evaluated new forecasting methods. Development produced a suite of tools covering rainfall timing, drought conditions and livestock heat and cold stress. Extension was delivered through a network of regional Climate Mates, workshops, one-on-one engagement and digital resources.

Key results include significant improvements in awareness, knowledge and use of climate information, with all adoption targets exceeded. Over 73,000 stakeholders were reached and more than 11,000 producers directly engaged, with awareness, knowledge and practice-change targets exceeded by 441%, 941% and 115%, respectively.

An independent evaluation of the Northern Australia Climate Program estimated average attributable benefits of \$1.55 per head across NACP Phases 1-3, with peak adoption projected across 2.54 million head of cattle and attributable on-farm benefits generating a Net Present Value of \$53.08 million. These benefits were associated with improved climate-informed decision-making and adoption of climate forecasting tools and services.

NACP3 uniquely integrated climate science, product development and extension within a single climate service framework, enabling continuous feedback between producers, researchers and developers.

The project established a practical climate service system, decision-support tools, extension capability and operational products that can continue to support climate-informed decision-making and drought resilience across the northern Australian red meat industry into the future.

Executive summary

Background

The Northern Australia Climate Program (NACP3) was undertaken to address the limited use of climate information by red meat producers in northern Australia. Despite the availability of forecasts, adoption has historically been constrained by prediction accuracy, limited relevance to farm decisions, and lack of confidence in interpretation. The project targeted producers and the broader red meat supply chain to improve decision-making and resilience. The results are intended to support ongoing delivery of climate services across northern Australia and inform future investment in forecasting and extension.

Objectives

The project aimed to:

- Improve the science and application of sub-seasonal and seasonal forecasting relevant to the northern Australia red meat industry
- Develop targeted decision-support tools for producers and policy-makers to support decision-making related to drought and climate variability
- Increase adoption and use of climate forecast information across the northern Australian grazing industry through integrated extension and training

The research component delivered significant advances in climate science and forecasting applications; however, these were not fully translated into improvements in operational forecasting skill within the project timeframe, reflecting the external operational processes and decision-making frameworks governing implementation within the Bureau of Meteorology and UK Met Office.

Methodology

The project was delivered through an integrated Research-Development-Extension (RD&E) approach:

- Research improved understanding of climate drivers and evaluation of climate forecasting systems, including prediction performance relevant to northern Australia and future pathways for operational forecasting systems.
- Development translated these advances into practical decision-support tools, including rainfall timing, drought monitoring and prediction, and livestock thermal stress products, and progressed selected tools towards operational deployment
- Extension delivered these tools to producers and stakeholders through the Climate Mates network, workshops, training programs, case studies, and digital platforms (including web-based tools, location-based visualisations and forecast interfaces), ensuring application in real-world decision-making

Results/key findings

The project delivered:

- Significant advances in researcher understanding of climate drivers and forecasting system performance, including improved evaluation of sub-seasonal and seasonal prediction systems
- Development and testing of seven prototype and two operational climate decision-support products, including rainfall onset, drought monitoring and prediction, and livestock stress tools
- Operationalisation of two forecast products (Northern Rainfall Onset and Rainfall Burst forecasts) through Bureau of Meteorology systems
- Demonstrated increased use of climate information in industry decision-making. All producer adoption targets were exceeded, with strong improvements in awareness, knowledge and practice change

Benefits to industry

Independent evaluation undertaken by Lee Beattie Consulting estimated average attributable benefits of \$1.55 per head across NACP Phases 1-3 (\$1.62 for Phase 3 only), with peak adoption projected across approximately 2.54 million head of cattle and attributable on-farm benefits generating a Net Present Value (NPV) of \$53.08 million (2020-45 benefits discounted at 5% to a 2025 baseline). Benefits were generated through improved climate-informed decision-making and increased adoption and use of climate forecasting tools, products and services. 5,644 producers reported that their knowledge had improved, and 229 reported that they had changed their practices.

The project improved the confidence of northern Australian red meat producers and policy-makers to use climate observations and forecasts, supporting more informed management decisions and improved consideration of climate-related risk. Evidence from extension evaluation and case studies demonstrated increased awareness, knowledge and application of climate information across participating stakeholders. Independent evaluation also found improvements in producer ability to manage risk, drought preparedness, resilience to climate variability and confidence in applying climate information to operational decision-making.

The project established two operational forecast products, along with training resources and producer use cases that will continue to support industry into the future. It also demonstrated the value of an integrated climate service approach, combining research, product development and extension, delivered through community-based trusted advisors.

Independent evaluation also identified broader environmental and social benefits associated with improved use of climate information. Environmental benefits included improved drought preparedness, resilience to climate variability, improved grazing management and reduced risk of land degradation. Social benefits included increased producer confidence, improved ability to manage risk, reduced stress levels and improved animal welfare outcomes.

Collectively, these findings demonstrate that industry value extends beyond direct production outcomes to include improved preparedness, resilience, risk management capability and confidence in climate-informed decision-making.

These findings are also consistent with published research demonstrating that seasonal climate forecasts can increase grazing enterprise profitability through improved management decisions, highlighting the broader value proposition associated with climate-informed decision-making.

Headline Impact Statement

Independent evaluation of the Northern Australia Climate Program (Phases 1-3 inclusive) estimated average attributable benefits of \$1.55 per head (\$1.62 for Phase 3 only), with peak adoption projected for 2026-2029 across approximately 2.54 million head of cattle. Improved climate-informed decision-making and adoption of climate forecasting tools and services generated an estimated NPV benefit of \$53.08 million (2020-45 benefits discounted at 5% to a 2025 baseline).

Future research and recommendations

Future work should focus on improving, operationalising and translating forecast capability, including through machine learning, maintaining and enhancing climate tools, and securing the long-term delivery of climate services such as the Climate Mates network.

Continued investment in integrated platforms, extension capability and institutional support will be required to sustain and scale industry benefits. The integrated climate service system developed through NACP3 provides a strong foundation that could be extended nationally, supporting broader application of climate-informed decision-making across Australian agriculture.

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1. Background

The northern Australian red meat industry operates in a highly variable climate, where rainfall variability, drought, and extreme weather and climate events strongly influence pasture availability, livestock condition, and enterprise profitability. While seasonal climate forecasts have been available for several decades, their adoption into management decisions has remained limited. This reflects a combination of factors, including variable forecast skill, limited alignment with operational decision-making, challenges in interpreting probabilistic information, and a lack of trusted support for application.

Research has demonstrated that while climate information has the potential to improve productivity and reduce risk, uptake remains inconsistent unless forecasts are tailored to local conditions, aligned with decision needs, and supported through extension (Cobon et al., 2021; Cowan et al., 2022).

The primary question addressed by NACP3 was: how can climate science, forecasting systems and extension be integrated to improve the use of climate information in producer decision-making? This question reflects a recognised gap between advances in climate science and their practical application in agriculture. The program targeted northern Australian beef producers and the broader supply chain (including advisors, policy-makers, corporate operations and service providers), as this group experiences high exposure to climate risk and stands to benefit most from improved climate-informed decision-making. The results of NACP3 were intended to be used to improve forecast systems, develop decision-support tools tailored to grazing systems, and establish delivery mechanisms that enable sustained adoption of climate information.

NACP3 is unique in its integrated approach, combining research, development and extension within a single program. Unlike traditional projects that focus solely on improving forecast models or delivering climate monitoring and forecast tools, NACP3 links improvements in fundamental climate science with the development of user-focused products and a dedicated extension network (Climate Mates) that supports adoption at the regional scale. This approach enables continuous feedback between producers, scientists and developers, ensuring that products remain relevant and usable. In addition, the program incorporated an integrated climate service system spanning forecast model improvements, development of decision-support tools, digital delivery systems (including web-based tools, location-based visualisations and forecast interfaces) and training programs, which distinguishes it from other initiatives that address only individual components of the climate information value chain.

2. Objectives

The purpose of NACP3 was to improve drought preparedness and climate risk management across the northern Australian red meat industry through an integrated Research-Development-Extension system. Specifically, the project had the following objectives:

- **Research:** Improve the basic science and application of sub-seasonal (multi-week) and seasonal climate forecasting systems of direct relevance to the northern Australian red meat industry
- **Development:** Developing targeted decision-support products for producers and policy-makers to support decision-making related to drought and weather-to-climate variability
- **Extension:** Integrate and embed climate forecast information within Northern Australian grazing industry networks to improve resilience to drought and weather-climate variability

The development and extension objectives were achieved in full. The research component delivered significant advances in climate science and forecasting applications; however, these were not fully translated into improvements in operational forecasting skill within the project timeframe, reflecting external operational processes and decision-making frameworks governing implementation within the Bureau of Meteorology and UK Met Office.

The project delivered improvements in understanding and application of climate forecasting systems, a comprehensive suite of decision-support tools, and a scaled extension program that exceeded all adoption targets. Awareness, knowledge and practice change targets (Category A, B and C) were significantly surpassed, demonstrating effective uptake and application of project outputs across the red meat industry of northern Australia.

3. Methodology

NACP3 adopted a vertically integrated Research-Development-Extension (RD&E) methodology, designed to link improvements in climate science with practical tools and industry adoption. This approach enabled continuous feedback between researchers, product developers and end users, ensuring that outputs were both scientifically robust and relevant to industry needs.

The program was delivered through a partnership between key organisations contributing across Research, Development and Extension. The University of Southern Queensland (UniSQ) led program integration, product development and extension delivery. The Bureau of Meteorology and the UK Met Office contributed primarily to the Research component through forecasting system development, model evaluation and analysis, and supported pathways towards operational implementation.

Development and integration activities were undertaken collaboratively, translating research outputs into decision-support tools aligned with industry needs. Extension delivery was conducted through the Climate Mates network, comprising regionally based advisors working with producers, industry groups and service providers, ensuring co-design of products, real-world testing, and translation of climate information into practical decision-making.

The integrated RD&E system was implemented through iterative cycles of model evaluation, product development and user engagement. Research findings informed the design of decision-support tools, which were refined through stakeholder feedback and tested in real-time applications. Extension activities ensured that products were translated into practical use by industry, with ongoing feedback informing refinement and supporting pathways towards operational implementation.

3.1 Research Methodology

The Research component focused on improving understanding and application of climate prediction systems relevant to northern Australian grazing systems. This included:

- Development and evaluation of a new convection parametrisation scheme (CoMorph) within global coupled modelling systems

- Evaluation of seasonal and sub-seasonal forecasting systems (e.g. ACCESS-S2) using hindcasts and case studies
- Investigation of key climate drivers, including El Niño Southern Oscillation (ENSO), Madden-Julian Oscillation (MJO), and monsoon variability
- Analysis of high-impact events such as droughts, heatwaves, floods and tropical systems
- Assessment of emerging machine learning forecasting systems alongside traditional numerical models

This methodology enabled identification of strengths and limitations in current forecasting systems and provided evidence to guide future development, including the potential role of machine learning approaches.

Lessons learned:

- Improved understanding of forecast skill limitations highlighted the need for continued development and integration of emerging forecasting approaches

3.2 Development Methodology

The Development component focused on translating research outputs into practical decision-support tools. The methodology included:

- Co-design of products with input from producers, advisors and industry stakeholders
- Development and enhancement of climate indices and decision-support tools (e.g. drought indicators, rainfall retreat, green date and livestock thermal stress indices).
- Integration of forecast and observational datasets to improve usability and relevance
- Iterative testing, validation and refinement using historical data and real-time applications
- Deployment of prototype tools through a web-based delivery systems for live testing
- Progression of selected products towards operational implementation

This approach enabled rapid development of tools aligned with industry needs, with iterative feedback ensuring relevance, usability, and practical value.

Lessons learned:

- Early consideration of operationalisation requirements is critical to ensure longevity of products beyond the project timeframe

3.3 Extension Methodology

The Extension component focused on increasing adoption and use of climate information through direct engagement with industry. The methodology included:

- Deployment of Climate Mates as regionally based trusted advisors

- Delivery of workshops, field days and training programs (including the PGS Supported Learning Package)
- One-on-one engagement with producers and industry stakeholders
- Use of digital communication channels, including webinars, online training and climate updates
- Implementation of a Customer Relationship Management system (HubSpot) to track engagement and outcomes
- Structured monitoring and evaluation using Category A (awareness), Category B (knowledge) and Category C (practice change) metrics

This approach enabled both localised engagement and broad-scale reach, supporting measurable improvements in awareness, knowledge and practice change across the industry.

Lessons learned:

- Trusted, regionally based advisors are critical to translating climate information into practical decision-making

3.4 Integration and Effectiveness

A key feature of the methodology was the integration across the RD&E components. Continuous feedback between these components enabled refinement of products based on user needs and improved relevance and usability.

This integrated approach enabled the program to deliver extension advice and products that were co-designed by producers and researchers. This ensured researchers had context for producer decision-making, and producers better understood the limitations of the science, improving relevance and usability of outputs.

4. Results

NACP3 delivered a comprehensive set of research, development and extension outcomes, resulting in the development and demonstration of an integrated climate service system for the northern Australian red meat industry.

4.1 Research Results

While the NACP3 team did not control operational implementation within the Bureau of Meteorology or UK Met Office, the Research component generated key findings that informed the future development of operational climate forecasting systems, improving the relevance of climate forecasts for northern Australian red meat producers.

4.1.1 New configuration for a future coupled modelling system

- Testing a new convection scheme, CoMorph (developed by UniSQ in collaboration with the Bureau and UK Met Office), within the future operational Global Coupled (GC) model, showed improvements over northern Australia, MJO prediction and in tropical cyclone forecasts (Zhu et al. 2024).
- Testing the convective scheme in the newer GC5 model version has shown more realistic features associated with historical tropical depressions and cyclone events over northern Australia, compared to GC5 forecasts conducted without CoMorph (NACP3 Milestone 9 Report).

4.1.2 Forecast system performance

- Research improved understanding of rainfall variability, drought processes and key climate drivers, including ENSO and the MJO, with implications for seasonal prediction in northern Australia (Cowan et al. 2023).
- Analysis of high-impact events (e.g. floods, tropical cyclones and droughts) highlighted the complexity and variability of these systems, indicating limitations in predictability, particularly for extreme events and slow-moving systems (Wang et al. 2026).

4.1.3 Machine learning forecasting

- Machine learning systems, including AIFS and GraphCast, demonstrated strong skill, particularly at longer lead times (beyond 7 days) (de Burgh-Day et al., in preparation).
- Case studies showed early-warning capability for extreme rainfall events at lead times of 10-12 days (de Burgh-Day et al., in preparation).
- Comparative analysis identified complementary strengths between dynamical and machine learning approaches (de Burgh-Day et al., in preparation).

4.1.4 Climate change projections

- New analyses identified increasing risks of livestock heat stress under future climate scenarios (Taylor et al., submitted).
- Projections also indicated reduced occurrence of livestock cold stress in some regions over time (Taylor and Cowan, in preparation).

4.1.5 Research outputs (intellectual property)

- A total of 93 publications are included across published, submitted and in-preparation outputs (Appendix 1 – NACP Publications (published, submitted and in preparation)).

These publications include outputs generated across the NACP, including earlier phases, as well as work completed during NACP3.

- Includes peer-reviewed journal articles, conference papers and technical reports covering climate drivers, drought processes, forecasting systems and industry applications

4.2 Development Results

The Development component produced a suite of prototype decision-support products and digital delivery systems, including two operational products.

Two forecast products (Northern Rainfall Onset and Rainfall Burst forecasts) were operationalised through Bureau systems, with the remaining products delivered as validated prototypes.

4.2.1 Product suite (intellectual property)

The following products were developed or further enhanced, validated and deployed (Table 1) and align with the seasonal grazing decision cycle (Fig. 1). Figure 1 illustrates how these climate products correspond to key stages and risks across the seasonal grazing cycle, rather than representing a strictly linear sequence of events.

- Northern Rainfall Onset (NRO) forecasts
- Rainfall Burst forecasts
- Green Date / Green Break of Season tools
- Drought Monitor and Combined Drought Indicator (CDI)
- Drought Outlook (1 and 3 month forecasts, with extension to longer lead times under development)
- Cattle thermal stress 7-day forecasts (including the Cattle Comfort Index, Temperature Humidity Index, Heat Load Index and Accumulated Heat Load Unit)
- Livestock Chill Index 7-day forecasts
- Flash drought monitoring system
- Northern Rainfall Retreat tool

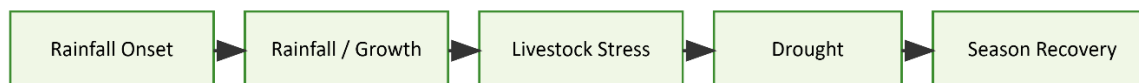
Key development outputs are summarised in Table 1.

Table 1. NACP product suite

Product	Purpose	Status
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Northern Rainfall Onset (NRO)	Predict if growing season start will be early or late	Operational
Rainfall Burst	Identify chance of significant rainfall over a 3-day period	Operational
Green Date	Indicate pasture growth timing	Prototype
Drought Monitor (CDI)	Monitor drought conditions	Prototype
Drought Outlook	Forecast drought risk	Prototype
Cattle Thermal Stress	Manage heat-related risk in livestock	Prototype
Livestock Chill Index	Manage cold stress risk in livestock	Prototype
Flash Drought	Rapid drought identification	Monitoring prototype only (no forecast capability)
Northern Rainfall Retreat	End of wet season	Prototype

Figure 1. Integration of climate products with key stages of the seasonal grazing decision cycle, showing how different products inform decision-making across the season.



4.2.2 Product performance and validation

- Forecast products were validated using historical datasets and real-time case studies
- Improvements were demonstrated in:
 - rainfall onset prediction
 - livestock thermal stress forecasting
 - drought monitoring accuracy
- Seamless forecasting approaches improved consistency across time scales

4.2.3 Digital platform and delivery systems

The program delivered a publicly available digital platform for testing and delivering prototype climate tools. Systems prototyped for potential operationalisation in subsequent projects include:

- Web-based product delivery system (www.nacp.org.au)
- Location-based monitoring and forecasting services (updated daily)
- AI-supported advisory functionality (developed and tested during NACP3; currently not deployed publicly)
- NACP Assistant chatbot
- Administrative dashboard for platform management

4.2.4 Product usage and engagement metrics

Product engagement was demonstrated through:

- Over 73,000 total stakeholder interactions across workshops, digital platforms, and communications
- Widespread use of web-based tools and monthly climate updates
- Increased awareness and application of location-specific forecasts in decision-making
- Consistent utilisation of climate tools and information products across multiple delivery channels, including digital platforms and advisor-led engagement

Monitoring and evaluation results indicated strong improvements across awareness, knowledge and practice change metrics. Qualitative feedback from Climate Mates highlighted consistent use of climate tools in advisory services across regions.

Independent evaluation of 2025 extension delivery indicated positive on-farm benefits associated with improved use of climate information, with benefits increasing through adoption across the northern Australian herd. The evaluation found that producers reported improved ability to manage risk, reduced stress levels, improved drought preparedness, enhanced resilience to climate variability and improved animal welfare outcomes. It also highlighted the critical role of trusted extension services and decision-support tools in translating climate information into practical management actions.

4.2.5 Product limitations

- Flash drought forecasting capability was not achieved due to model and data constraints.
- Monitoring capability was successfully implemented instead.
- The AI-supported advisory functionality was paused following testing to refine its performance and ensure alignment with best-practice advisory principles. Further development and testing are recommended to enhance this capability.

4.3 Extension Results

The Extension component delivered strong and measurable outcomes across awareness, knowledge and practice change.

4.3.1 KPI outcomes

Extension performance against targets is summarised in Table 2. Category A, B and C outcomes are derived from CRM records using the program's monitoring and evaluation framework. These metrics capture awareness, knowledge and practice change across all recorded engagement pathways (e.g. workshops, webinars, website interactions, email communications, media engagement and advisory activities).

Category A, B and C outcomes (Table 2) represent cumulative outcomes across all engagement pathways. In contrast, the extension activity summary (Table 3) reflects a defined set of engagement activities reported separately, primarily structured extension delivery activities such as workshops, field days, one-on-one meetings and training sessions.

Table 2. Final Category A, B and C outcomes (targets vs achieved)

Category	Target (Producers)	Achieved	% Achieved
Category A (Awareness)	6,000	26,454	441%
Category B (Knowledge)	600	5,644	941%
Category C (Practice Change)	200	229	115%

4.3.2 Engagement activities

The extension activity summary (Table 3) presents a defined set of extension activities delivered through the program, capturing direct engagement with stakeholders. These activities include climate workshops, presentations (including multi-topic workshops, field days and conferences), one-on-one meetings, training sessions, webinars, monthly climate updates and surveys.

These activities represent the core extension delivery mechanisms through which producers and stakeholders engaged with NACP products and services, contributing to the outcomes summarised in Table 2.

Table 3. Extension activity summary

Metric	Value
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Total activities delivered	939
Total stakeholders reached	73,344
Producers directly engaged	11,103

4.3.3 Case studies

Eight case studies were completed across a range of regions and production systems in northern Australia, providing a representative cross-section of grazing enterprises and climate conditions. The case studies demonstrate the practical application of climate information and decision-support tools in real on-farm settings and are intended to serve as evergreen adoption materials for continued use beyond the project's completion.

Across the case studies, producers reported improved confidence in interpreting climate information, more proactive and timely decision-making, and enhanced ability to manage climate-related risk. Common outcomes included improved stocking and grazing management decisions and better alignment of operations with seasonal conditions.

Case study findings were shared through workshops, presentations and training activities, supporting broader awareness and adoption beyond the participating producers.

Collectively, these case studies demonstrate that climate-informed decision-making can be effectively applied across a wide range of northern Australian grazing systems.

Case study activities also contributed to peer-reviewed research outputs, including studies on livestock chill index, Channel Country grazing systems, and heat stress events in southern Queensland.

4.3.4 Extension system outputs (intellectual property)

These outputs represent extension system assets that support delivery and adoption of climate products, rather than the products themselves.

- Climate Mate extension service and training materials
- Profitable Grazing Systems (PGS) Supported Learning Package
- Training manuals, presentations and digital learning resources
- CRM-based engagement and monitoring system

4.4 Integrated Outcomes

The combined RD&E outputs resulted in:

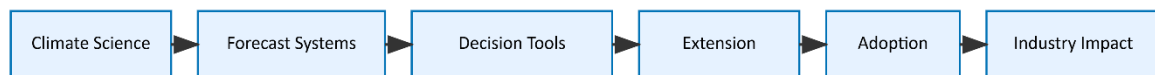
- An integrated climate service system (Fig. 2)
- Alignment between scientific capability, product delivery and industry use

- Demonstrated translation of research into practice

Environmental benefits were observed through improved grazing management, including better groundcover maintenance and reduced risk of land degradation.

This integrated outcome represents a key result of the program, distinguishing it from projects delivering isolated tools or research outputs.

Figure 2. Integrated climate service system linking research, development and extension to industry impact.



These outcomes collectively demonstrate how climate science can be translated into a practical decision-support capability for the red meat industry.

Independent evaluation of NACP Phases 1-3 demonstrated that these integrated outcomes translated into measurable industry value. The evaluation estimated attributable benefits of \$1.55 per head (\$1.62 for Phase 3 only), peak adoption in 2026-2029 across approximately 2.54 million head of cattle, and a Net Present Value (NPV) of \$53.08 million (2020-45 benefits discounted at 5% to a 2025 baseline) attributable to improved climate-informed decision-making and adoption of forecasting tools and services.

5. Conclusion

The Northern Australia Climate Program Phase 3 (NACP3) demonstrated the value of an integrated climate service system that addresses key limitations in the use of climate information within the northern Australian red meat industry. Independent evaluation across NACP Phases 1-3 estimated attributable benefits of \$1.55 per head, peak adoption across approximately 2.54 million head of cattle and a NPV of \$53.08 million from improved climate-informed decision-making and adoption of climate forecasting tools and services.

The program delivered substantial value through improved decision-making and risk management. Independent evaluation identified positive economic benefits associated with improved use of climate information and highlighted the importance of integrated climate services, including Climate Mates, in enabling adoption and realising value from climate information. 5,644 producers reported that their knowledge had improved, and 229 reported that they had changed their practices.

A key insight from the project is that adoption of climate information depends not only on forecast skill, but also on relevance, usability and support for interpretation. The Climate Mate extension service, combined with digital delivery systems and training (including the PGS package), enabled widespread engagement and measurable practice change. The establishment of a suite of decision-support tools covering rainfall timing, drought conditions and livestock thermal stress has improved the capacity of producers to manage climate risk. At the same time, the program identified that forecast skill for extreme events remains a limitation, and that continued improvement in forecasting capability is required.

The project has also identified important opportunities for future value, including areas where further investment would be expected to deliver additional economic and industry benefits:

- Improving prediction of high-impact events at subseasonal (weeks 3-4) and longer lead times;
- Further development and operationalisation of tools to support ongoing impact and broader adoption
- Ongoing support and scaling of the Climate Mate network across regions and industries
- Continued evaluation and integration of machine learning approaches into operational forecast systems.

Overall, NACP3 has established a clear pathway to ongoing value to the red meat industry of northern Australia through improving confidence in climate information, supporting more informed decision-making, and establishing systems and resources that can continue to deliver benefits into the future.

All development and extension milestones were completed in full. The research component delivered substantial advances, though not all forecast improvements were operationalised within the project timeframe.

5.1 Key findings

- The integrated Research-Development-Extension system was highly effective in translating climate science into practical decision-support tools and services for the red meat industry
- Adoption of climate information increased significantly when forecasts were user-focused, and supported through trusted extension
- A suite of prototype climate tools was successfully developed and tested across the grazing cycle, with two products operationalised through Bureau systems
- All adoption targets were exceeded, demonstrating substantial improvements in awareness, knowledge and practice change among producers and industry stakeholders. Independent evaluation identified positive economic benefits associated with improved use of climate information and highlighted the critical role of Climate Mates and trusted extension services in supporting adoption, risk management and value realisation.
- Standalone evergreen outputs were established, including the Climate Mate network, Profitable Grazing Systems (PGS) package, case study materials, and operational forecast products, which can continue to deliver value beyond the project timeframe
- The Climate Mate extension service proved to be an effective mechanism for building trust and supporting climate-informed decision-making
- Machine learning forecasting systems showed strong potential, particularly at longer lead times
- Forecasting high-impact events remains a key limitation requiring further development
- The program successfully demonstrated an integrated climate service system linking products, extension, training and digital delivery
- Long-term sustainability of outputs will require continued investment in data, infrastructure and institutional ownership.

5.2 Benefits to industry

Practical application and recommendations

- Red meat producers can apply operational and ongoing outputs (including Bureau-supported products, PGS materials and Climate Mate advice) to inform stocking, grazing and climate risk management decisions
- Adoption is most effective when supported through extension networks (e.g. Climate Mates) and training programs such as PGS
- Continued use of location-based and forecast-integrated tools is recommended to support property-level decision-making
- Ongoing investment is required to maintain and enhance tools and services, including improvements in data integration, usability and forecasting capability

Benefits to Australian agriculture

- Independent evaluation of NACP Phases 1-3 estimated average attributable benefits of \$1.55 per head, with peak adoption projected across approximately 2.54 million head of cattle and attributable on-farm benefits generating a NPV of \$53.08 million. These benefits were associated with improved climate-informed decision-making and adoption of climate forecasting tools and services.
- The program has improved confidence in the use of climate information, supporting more informed and timely decision-making. 5,644 producers reported that their knowledge had improved, and 229 reported that they had changed their practices.
- Adoption of climate-informed practices has reduced exposure to climate-related risk and supported improved resilience
- Environmental benefits have been demonstrated through improved land management, including better groundcover maintenance and reduced risk of land degradation
- The integrated climate service system provides a scalable model for delivering climate services across Australian agriculture
- Legacy systems established through the program, including the Climate Mate network, PGS training package and digital platforms, provide a foundation for ongoing adoption and capability building
- Independent evaluation also identified broader environmental and social benefits associated with improved use of climate information, including improved drought preparedness, resilience to climate variability, improved grazing management, reduced land degradation risk, increased confidence in decision-making, improved risk management capability, reduced producer stress and improved animal welfare outcomes.
- Across the independent evaluations, increasing adoption and utilisation of climate information highlighted the importance of trusted extension services, including the Climate Mates network, and practical decision-support tools in translating climate science into on-farm value and industry impact.
- Published research has demonstrated that improved use of seasonal climate forecasts can increase grazing enterprise profitability through improved management decisions, providing additional evidence that the benefits of climate-informed decision-making extend beyond direct production outcomes to broader economic, environmental and social benefits across the red meat supply chain.

5.3 Independent Evaluation of Program Impact

An independent evaluation undertaken by Lee Beattie Consulting assessed the attributable impacts of the Northern Australia Climate Program (NACP) across Phases 1-3 using a consistent methodology aligned with MLA evaluation requirements.

The assessment estimated average attributable benefits of \$1.55 per head, with peak adoption projected across approximately 2.54 million head of cattle. Attributable on-farm benefits were estimated to generate an NPV of \$53.08 million. Benefits were attributed to improved climate-informed decision-making and increased adoption and use of climate forecasting tools, products and services.

The evaluation also identified broader environmental and social benefits, including improved drought preparedness, resilience to climate variability, improved grazing management, reduced land degradation risk, increased confidence in decision-making, reduced producer stress, improved risk management capability and improved animal welfare outcomes.

These findings provide independent evidence that the integrated climate service model developed through NACP has delivered substantial value to the northern Australian red meat industry. They also support continued investment in climate-informed decision-making, forecasting services, product development and trusted extension networks to sustain and expand industry benefits into the future.

6. Future research and recommendations

Key challenges and successes

The project demonstrated that an integrated climate service system can significantly improve the adoption and use of climate information in the red meat industry. The strong performance of the Climate Mate extension service, combined with user-focused tools and digital delivery platforms, represents a key success supporting future investment in this area.

However, several challenges were identified that require ongoing attention. These include limitations in forecasting high-impact and extreme events, dependence on external data and computational infrastructure, and the need to further simplify and integrate tools for end users. In addition, while machine learning forecasting systems show strong potential, they remain at an early stage of operational application and require further development, testing and validation.

Future research and development

- Continue investment in machine learning forecasting systems to improve capability, particularly for high-impact events and longer lead times (weeks 3-4 and beyond seasonal timescales)
- Improve prediction of high-impact events through integration of emerging forecast approaches, rather than replication of existing research efforts
- Expand focus on compound climate risks as a priority area for future development
- Improve integration of climate, pasture and livestock systems modelling to support whole-of-enterprise decision-making
- Enhance validation and benchmarking of forecast products to support confidence, usability and progression towards operational implementation

Practical application of project insights

- Integrate climate tools and forecasts into routine property-level decision-making, particularly for grazing and stocking strategies, supported by trained and operationally supported local advisors.
- Promote use of location-specific and seamlessly integrated forecast products to improve responsiveness to changing seasonal conditions.
- Embed climate information within broader farm business planning and risk management processes

Development and adoption activities

- Maintain and expand extension networks, including the Climate Mates, to support ongoing adoption and climate resilience
- Embed the PGS training package within MLA and industry delivery programs to build long-term capability
- Continue development of integrated digital platforms to provide a single point of access for climate tools, information and advisory support
- Secure ongoing funding and institutional ownership to maintain, update and scale the climate service system.

7. References

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Pacific and Australian regions. Journal of Southern Hemisphere Earth Systems Science.
<https://doi.org/10.1071/ES23011>.

Additional project outputs

A complete list of publications associated with the NACP is provided in Appendix 1 (published, submitted and in preparation; total = 93 outputs)

8. Appendix

8.1 Appendix 1 – NACP Publications (published, submitted and in preparation)

This list includes publications generated across the NACP, including work initiated under earlier phases and completed during NACP3.

No.	Short title	Title	Authors	Journal / Pub date
NACP2:				
1.	Flash drought	Using the evaporative stress index to monitor flash drought in Australia	Nguyen H, Wheeler, Otkin, Cowan, Frost, Stone R	Envir Res Lett 14, (6) 2019 https://doi.org/10.1088/1748-9326/ab2103
2.	Shifts in CV in pastoral zone	Evaluating the shifts in rainfall and pasture growth variabilities across the Pastoral zone of Australia during the 1910-2010 period	Cobon, Kouadio, Mushtaq, Jarvis, Carter, Stone G, Davis	Crop & Pasture Science 70, 634-647 (2019) https://doi.org/10.1071/CP18482
3.	Qld floods	Forecasting the extreme rainfall, low temperatures, and strong winds associated with the northern Queensland floods of February 2019	Cowan, Wheeler, Alves, Narsey, de Burgh-Day, Griffiths, Jarvis, Cobon	WACE / 2019 (vol 26) https://doi.org/10.1016/j.wace.2019.100232
4.	Value of seasonal forecasts	Valuing seasonal climate	Cobon, Darbyshire, Crean, Kodur,	WCAS 12, 3-14 (2020) https://doi/pdf/10.1175/WCAS-D-19-0018.1

		forecasts in the northern Australia beef industry	Simpson, Jarvis	
5.	Tropical convection	ETIN-MIP Extratropical-Tropical Interaction Model Intercomparison Project – Protocol and Initial Results	Kang, Hawcroft, Xiang, Hwang, and others	Bull. Amer. Meteor. Soc., 100, 2589–2606 https://doi.org/10.1175/BAMS-D-18-0301.1
6.	Multi-year variability	Mechanisms for multiyear variations of northern Australia wet-season rainfall	Sur, Sharmila, H. Hendon	Nature Scientific Report, (2020) 10 5086, https://doi.org/10.1038/s41598-020-61482-5
7.	Flash drought	Flash droughts present a new challenge for subseasonal-to-seasonal prediction	Wheeler is a co-author among many from around the world	Nature Climate Change 2020, https://doi.org/10.1038/s41558-020-0709-0
8.	Value of spatial diversification	Integrating climate information and spatial diversification increases grazing profitability and decreases risk	Thong Nguyen-Huy, Jarrod Kath, Shahbaz Mushtaq, David Cobon, Gordon Stone & Roger Stone	Agronomy for Sustainable Development 2020, 40: 4 https://doi.org/10.1007/s13593-020-0605-z
9.	NRO forecasts using ACCESS-S1	Improving the seasonal prediction of Northern Australian rainfall onset to help with grazing management decisions	Cowan. T., R. Stone, M. Wheeler, and M. Griffiths	Climate Services, 19, 100182, https://doi.org/10.1016/j.cliser.2020.100182
10.	High-res simulation of Tropical cyclone genesis	Real world and tropical cyclone world. Part I: high-resolution climate model verification	S. Sharmila, KJE Walsh, M Thatcher, S Wales, S Utembe	J. Climate, 33, 1455-1472 (2020) https://doi.org/10.1175/JCLI-D-19-0078.1
11.	Simulation of Tropical cyclone genesis	Real world and tropical cyclone world. Part II:	KJE Walsh, S. Sharmila, M Thatcher, S Wales, S	J. Climate, 33, 1473-1486 (2020) https://doi.org/10.1175/JCLI-D-19-0079.1

	in Aqua-planet configuration	sensitivity of tropical cyclone formation to uniform and meridionally-varying sea surface temperatures under aquaplanet conditions.	Utembe, A Vaughan	
12.	Qld native pastures, beef and a changing climate	Native pastures and beef cattle show a spatially variable response to a changing climate in Queensland, Australia	David H Cobon, Grant Stone, John Carter, Greg McKeon, Baisen Zhang, Hanna Heidemann	European Journal Agronomy 2020 114 https://doi.org/10.1016/j.eja.2020.126002
13.	Drought index	Climatology and variability of the evaporative stress index (ESI) and its suitability as a tool to monitor Australian drought	Nguyen H, Otkin, Wheeler, Hope, Trewin, Pudmenzky	Journal Hydro Meteorology (2020) 21, 2309-2324. https://DOI: 10.1175/JHM-D-20-0042.1
14.	Aerosol Impacts on Clouds, Precipitation, and Radiation	Are Changes in Atmospheric Circulation Important for Black Carbon Aerosol Impacts on Clouds, Precipitation, and Radiation?	B. T. Johnson, J. M. Haywood, M. K. Hawcroft	J Geophysical Research Atmospheres 124 (14), 7930-7950 https://doi.org/10.1029/2019JD030568
15.	Walker circulation	Walker circulation response to extratropical radiative forcing	Kang, Xie, Shin, Kim, Hwang, Stuecker, Xiang, Hawcroft	Science Advances (2020), 6, DOI: https://doi.org/10.1126/sciadv.abd3021
16.	Accumulated rainfall in tropical cyclones	Global climatology of rainfall rates and life-time accumulated rainfall in	Lavender,SL, McBride, JL	Inter. J. Climatology 2020; 1-19 https://doi.org/10.1002/joc.6763

		tropical cyclones: Influence of cyclone basin, cyclone intensity and cyclone size		
17.	Tropical cyclones in Australia	Review of tropical cyclones in the Australian region: Climatology, variability, predictability, and trends	Savin S. Chand Andrew J. Dowdy Hamish A. Ramsay Kevin J. E. Walsh Kevin J. Tory Scott B. Power Samuel S. Bell Sally L. Lavender Hua Ye Yuri Kuleshov	WIREs Climate Change 2019 https://doi.org/10.1002/wcc.602
18.	The Ocean-Monsoon	The Influence of Interannual and Decadal Indo-Pacific Sea Surface Temperature Variability on Australian Monsoon Rainfall	Heidemann, H., J. Ribbe, B. J. Henley, T. Cowan, C. Pudmenzky, R. Stone and D. H. Cobon.	Journal of Climate 2022 https://doi.org/10.1175/JCLI-D-21-0264.1
19.	Developing a combined drought indicator	A drought monitor for Australia	Guillory, L., Pudmenzky, Nguyen-Huy, T., C., Cobon, DH	Environmental Modelling & Software https://doi.org/10.1016/j.envsoft.2023.105852
20.	Dust bowl heatwaves I	Present-day greenhouse gases could cause more frequent and longer Dust Bowl heatwaves	Cowan T., S. Undorf, G. C. Hegerl, L. J. Harrington and F. E. L. Otto	Nature Climate Change 2020 https://doi.org/10.1038/s41558-020-0771-7
21.	Northern Australia Climate Program	Northern Australia Climate Program - Supporting adaptation in rangeland grazing systems through more	David Cobon, Chelsea Jarvis, Kate Reardon-Smith, Laura Guillory, Christa Pudmenzky, Shahbaz	Rangelands Journal – invited special issue on drought – Sept 2021, https://www.publish.csiro.au/RJ/RJ20074

		targeted climate forecasts, improved drought information and an innovative extension program	Mushtaq, Roger Stone	
22.	Dust bowl heatwaves II	Ocean and land forcing of the record-breaking Dust Bowl heatwaves across central United States	Cowan, T., Hegerl, G., Schurer, A., Tett, S., Vautard, R., Yiou, P., Jézéquel, A., Otto, F. E. L., Harrington, L.J. and Ng, B	Nature Communications 2020 https://doi.org/10.1038/s41467-020-16676-w
23.	Australia's future climate	Insights From CMIP6 for Australia's Future Climate	Grose M, Narsey S, Delage F, Dowdy A, Bador M, Boschat G, Chung C, Kajtar J, Rauniyar S, Freund M, Lyu K, Rashid H, Zhang X, Wales S, Trenham C, Holbrook N, Cowan T, Alexander L, Arblaster J, and S. Power	Earth's Future 2020 https://doi.org/10.1029/2019EF001469
24.	Skill of S2S models in predicting the Feb 2019 extreme rainfall.	Advances in the subseasonal prediction of extreme events	D. Domeisen, C. J. White, H. Afargan-Gerstman, Á. G. Muñoz, M. A. Janiga, F. Vitart, C. O. Wulff, S. Antoine, C. Ardilouze, L. Batté, H. C. Bloomfield, D. Brayshaw, S. J. Camargo, A. Charlton-Pérez, D.	Bulletin of the American Meteorological Society (BAMS) 2022, 103, https://doi.org/10.1175/BAMS-D-20-0221.1

			Collins, T. Cowan et al.	
25.	Value of seasonal forecasts	Insights into the value of seasonal forecasts to agriculture	R Darbyshire, J Crean, M Cashen, M Rajin, K Broadfoot, M Simpson, DH Cobon, C Pudmenzky, L Kouadio, S Kodur	Australian Journal of Agricultural and Resource Economics, 59, 1-25 https://doi.org/10.1111/1467-8489.12389
26.	Risk Management for climate resilience	Creating positive synergies between risk management and transfer to accelerate food system climate resilience.	Mushtaq, S., Kath, J., Stone, R. Henry, R. Laderach, P. Reardon Smith, K. Cobon D. et al.	Climatic Change 161, 465–478 (2020). https://doi.org/10.1007/s10584-020-02679-5
27.	Wet season bursts	Forecasting northern Australian summer rainfall bursts using a seasonal prediction system	Cowan, Wheeler, Sharmila, Narsey & de Burgh-Day	Weather and Forecasting (2022) https://doi.org/10.1175/WAF-D-21-0046.1
28.	ENSO impacts	Impacts of Low-Frequency Internal Climate Variability and Greenhouse Warming on El Niño–Southern Oscillation	Ng, B., Cai, W., Cowan, T., & Bi, D.	<i>Journal of Climate</i> , 34(6), 2205-2218.
29.	Flash drought	The 2019 flash droughts in subtropical eastern Australia and their association with large-scale climate drivers.	Nguyen H, Wheeler MC, Hendon HH, Lim E-P, Otkin JA	<i>2021 Weather and Climate Extremes</i> , 32, 100321.
30.	Tropical cyclone damage	Estimation of maximum seasonal tropical	Lavender, S.L., Walsh, K.J.E.,	Nat Hazards (2021). https://doi.org/10.1007/s11069-021-04977-2

		cyclone damage in the Atlantic using climate models	Utembe, S. et al.	
31.	Forecasting an Extreme Event: The Queensland Floods	The Benefits of Ensemble Prediction for Forecasting an Extreme Event: The Queensland Floods	Matt Hawcroft, Sally Lavender, Dan Copsey, Sean Milton, José Rodríguez, Warren Tennant, Stuart Webster, Tim Cowan	Monthly Weather Review, 2021, 149, 2391-2408 https://doi.org/10.1175/MWR-D-20-0330.1
32.	Flash drought	Development of a flash drought intensity index	Otkin, J. A., Y. Zhong, E. D. Hunt, J. I. Christian, J. B. Basara, H. Nguyen, M. C. Wheeler, T. W. Ford, A. Hoell, M. Svoboda, and M. C. Anderson	Atmosphere, 12, 741, http://dx.doi.org/10.3390/atmos12060741
33.	Long-range ENSO prediction	Variability of ENSO forecast skill in 2-year global reforecasts over the 20th Century	Westheimer, A., Balmaseda, M. A., Stockdale, T. N., Mayer, M., Sharmila, S., Hendon, H.H., Alves, O.	Geophysical Research Letters https://doi.org/10.1029/2022GL097885
34.	Long-range ENSO prediction	Contrasting El Niño–La Niña Predictability and Prediction Skill in 2-Year Reforecasts of the Twentieth Century	S. Sharmila, H. Hendon, O. Alves, A. Weisheimer, M. Balmaseda	Journal of Climate (2023), 36(5), 1269-1285, https://journals.ametsoc.org/view/journals/clim/36/5/JCLI-D-22-0028.1.xml
35.	Long-range ENSO prediction	Forecasting multi-year El Niño and La Niña events with ECMWF 20th century hindcasts	S. Sharmila, H. Hendon, O. Alves, A. Weisheimer, M. Balmaseda, M. Wheeler,	Under review

			W. Sharples, A. Marshall	
36.	Modelling Maritime Continent weat her features	Climatology of Borneo Vortices in the HadGEM3- GC3	Liang, J., Catto, J. L., Hawcroft, M., Hodges, K. I., Tan, M. L., & Haywood, J. M	<i>Journal of Climate</i> , 34(9), 3401-3419.
37.	Maritime Continent weat her/climate dynamics	Long-term trends in atmospheric rivers over East Asia	Liang, J., Yong, Y., Hawcroft, M.	<i>Climate Dynamics</i> (2023), 60, 643–666, https://doi.org/10.1007/s00382-022-06339-5
38.	Modelling Maritime Continent weat her features	Monsoonal precipitation over Peninsular Malaysia in the CMIP6 HighResMIP experiments: The role of model resolution	Liang, J., Tan, M. L., Hawcroft, M., Catto J.L., Hodges K.I., Haywood, J.M.	<i>Climate Dynamics</i> (2022) 58, 2783–2805 https://doi.org/10.1007/s00382-021-06033-y
39.	Flash drought	Climatology and historical occurrences of flash drought over Australia	Nguyen H., Wheeler M. C., Otkin J. A., Nguyen-Huy T., Cowan T.	<i>Journal of Hydrometeorology</i> (under review)
40.	Qld floods	Multi-week prediction of livestock chill conditions associated with the northwest Queensland floods of February 2019	Cowan T., Wheeler M., de Burgh-Day C., Nguyen H., Cobon D.	<i>Scientific Reports Sci Rep</i> 12, 5907 (2022). https://doi.org/10.1038/s41598-022-09666-z
41.	Subseasonal to seasonal forecasts	Sub-seasonal to seasonal climate forecasts provide the backbone of a near real-time Event Explainer service	Hope, P., M. Zhao, S. Abhik, G. Tolhurst, R. McKay, S. P. Rauniyar, L. Bettio, A. Ramchurn, E- P. Lim, A. S. Pepler, T. Cowan, A. Watkins	<i>Bulletin of the American Meteorological Society</i> (2022), 103, S7-S13, https://doi.org/10.1175/BAMS-D-21-0253.1 .

42.	MJO/ENSO rainfall impacts	The Combined Influence of the Madden–Julian Oscillation and El Niño–Southern Oscillation on Australian Rainfall	Cowan, T., Wheeler M., Marshall A.	J. Climate 36 (2), 313-334 (2023) https://doi.org/10.1175/JCLI-D-22-0357.1
NACP3:				
43.	MJO temperature impacts	Madden–Julian Oscillation Impacts on Australian Temperatures and Extremes	Marshall A., Wheeler M., Cowan, T.	J. Climate 36 (2), 335-357 (2023) https://doi.org/10.1175/JCLI-D-22-0413.1
44.	La Nina/ENSO Impacts	Why Australia was not wet during spring 2020 despite La Niña.	Lim, EP., Hudson, D., Wheeler, M.C. et al	Sci Rep 11, 18423 (2021). https://doi.org/10.1038/s41598-021-97690-w
45.	Multiyear prediction	Contrasting El Niño–La Niña predictability and prediction skill in 2-year reforecasts of the Twentieth Century	S. Sharmila, H. Hendon, O. Alves, A. Weisheimer, M. Balmaseda	J Climate 36 (5), 1269-1285 (2023) https://doi.org/10.1175/JCLI-D-22-0028.1
46.	Northern Australia Climate Program	The Northern Australia Climate Program: Overview and selected highlights	Sally Lavender, Tim Cowan, Matthew Hawcroft, Matthew C. Wheeler, Chelsea Jarvis, David Cobon, Hanh Nguyen, Debra Hudson, S. Sharmila, Andrew Marshall, Catherine de Burgh-Day, Sean Milton, Alison Stirling, Oscar Alves, and	BAMS 103 (11), E2492-E2505 (2022) https://doi.org/10.1175/BAMS-D-21-0309.1

			Harry H. Hendon	
47.	Multi-year variability	Queensland's multi-year Wet and Dry periods: implications for grazing enterprises and pasture resources.	McKeon G., Stone G., Ahrens D., Carter J., Cobon D., Irvine S., Syktus J.	2021 <i>Rangeland Journal</i> 43, 121-142. https://doi.org/10.1071/RJ20089
48.	Australian Monsoon variability	Variability and long-term change in Australian monsoon rainfall: A review	Heidemann H., Cowan T., Henley B. J., Ribbe J., Freund M., Power S.	WIREs Climate Change (2023), https://doi.org/10.1002/wcc.823
49.	MJO extreme temperature impacts	Madden-Julian Oscillation teleconnections to Australian springtime temperature extremes and their prediction in ACCESS-S1	Marshall A.G., G. Wang, H.H. Hendon, H. Lin	Climate Dynamics (2023, published online) https://doi.org/10.1007/s00382-022-06586-6
50.	GC5 evaluation	Biases and teleconnections in the Met Office Global Coupled Model Version 5.0 (GC5) – insights for seasonal prediction and Australia	Li C., Hudson D., Zhou X., Zhu H., Wheeler M. C., Young G., Marzin C., Roberts L.	Journal of Southern Hemisphere Earth Systems Science (2023), 73, 262-279, https://doi.org/10.1071/ES23010
51.	CoMorph testing	Impacts of the new UM convection scheme, CoMorph-A, over the Indo-Pacific and Australian regions	Zhu H., Hudson D., Li C., Shi L., White B., Young G., Stirling A., Whittall M., Lock A., Lavender S., Stratton R.	Journal of Southern Hemisphere Earth Systems Science (2024), 74, ES23011 https://doi.org/10.1071/ES23011
52.	CoMorph-A: Idealised testing	The use of idealised experiments in testing a new	Sally L. Lavender, Alison J. Stirling,	Quarterly Journal of the Royal Meteorological Society (QJRMS)(2024), https://doi.org/10.1002/qj.4660

		convective parameterization: Performance of CoMorph-A	Michael Whittall, Rachel Stratton, Chimene L. Daleu, Robert S. Plant, Adrian Lock, Jian-Feng Gu	
53.	CoMorph-A: Global testing	The performance of the CoMorph A convection scheme in global simulations with the Met Office Unified Model	Lock, A., Whittall, M., Stirling, A. J., Williams, K., Lavender, S. L., Morcrette, C., Matsubayashi, K., Field, P. R., Martin, G., Willett, M., Heming, J.	QJRM (2024), 150(763), 3527–3543, https://doi.org/10.1002/qj.4781
54.	Retreat in the Australian monsoon	Observing and forecasting the retreat of northern Australia's rainy season	Cowan, T., Hinds, E., Marshall, A., Wheeler, M. C., de Burgh-Day, C.	Journal of Southern Hemisphere Earth Systems Science (2024), 74, ES23022 https://doi.org/10.1071/ES23022 .
55.	Cattle heat stress, observations	Observed climatology and variability of cattle heat stress in Australia	Cowan, T., Wheeler, M. C., Cobon, D.H., Gaughan, J. B., Marshall, A.G., Sharples, W., McCulloch, J., Jarvis, C.	Journal of Applied Meteorology and Climatology (2024), https://doi.org/10.1175/JAMC-D-23-0082.1
56.	Australian monsoon rainfall trends	Asian Anthropogenic Aerosol Forcing Played a Key Role in the Multidecadal Increase in Australian Summer Monsoon Rainfall	Fahrenbach, N.L.S., Bollasina, M.A., Samset, B.H., Cowan, T., Ekman, A.M.L	Journal of Climate (2024), 37, 895-911, https://journals.ametsoc.org/view/journals/clim/aop/JCLI-D-23-0313.1/JCLI-D-23-0313.1.xml

57.	ENSO and multidecadal variability	Statistical relationships between the Interdecadal Pacific Oscillation and El Niño-Southern Oscillation	Heidemann, H., Cowan, T., Power, S.B., Henley, B.J.	Climate Dynamics (2023), https://doi.org/10.1007/s00382-023-07035-8
58.	Managing extreme weather risk	Seasonal Climate Forecast-An Important Tool in Managing the Risk of Extreme Weather Events in Australia's Wheat Industry	Luo, Q., Wen, L., Cowan, T., Schilling, D.	Agricultural and Forest Meteorology (2024), https://doi.org/10.1016/j.agrformet.2024.110005 .
59.	Climate change impacts at beef enterprises	Impacts of environmental feedbacks on the production of a central Queensland beef enterprise in a future climate	Duc-Anh An-Vo, David Cobon, Jo Owens, Adam Liedloff, Tim Cowan, Scott Power	Agricultural Systems (2024), 214, https://www.sciencedirect.com/science/article/pii/S0308521X23002433
60.	Climate change adaptation	Improving land condition improves farm profit under future climates	Duc-Anh An-Vo, Brendan Cullen, David Cobon, Matthew T. Harrison	In preparation
61.	FAIR drought monitor dataset	Making Australian Drought Monitor dataset findable, accessible, interoperable and reusable	Francis Gacenga, Duc-Anh An-Vo, Jillian McCulloch, Richard Young, David Cobon	Computers and Electronics in Agriculture (2024), 226, https://doi.org/10.1016/j.compag.2024.109381
62.	Hadley circulation	The Hadley circulation in a changing climate	Lionello P., D'Agostino R., Ferreira D., Nguyen H., Singh M.	Annals of the New York Academy of Sciences NYAS15114 (2024). https://doi.org/10.1111/nyas.15114

63.	Evapotranspiration in northern Australia	Evapotranspiration and carbon fluxes from a grazed Eucalypt savanna in northeast Australia: measurements from a highly instrumented flux-tower and sap flow monitoring site	Owens, J., A.W. Western, L. B. Hutley, A.J. Frost, T. Cowan, T. Doody, S. Levick, and C. Ewenz	Agricultural and Forest Meteorology, under review
64.	Drought in Australia	Physical mechanisms of drought development, intensification and termination: an Australian review	Holgate, C.M., Falster, G.M., Gillett, Z.E. et al.	Communications Earth & Environment, 6, 220 (2025). https://doi.org/10.1038/s43247-025-02179-3
65.	Green Break of Season and Green date	Exploring the Green Break of Season and Green Date over northern Australia	Naha, R., Cowan, T., C. Wheeler, M., Owens, J., Cobon, D., Jarvis, C.	Agricultural Systems (2026), 231, https://doi.org/10.1016/j.agsy.2025.104526
66.	Hunga Tonga and MJO	Interactions of large volcanic eruptions with the Madden Julian Oscillation	Lucas. C	Under review
67.	Drought Outlook	A Drought Outlook for Australia	Thong Nguyen-Huy, David Cobon, Tim Cowan, Sabin Maharjan, Hanh Nguyen, Matthew C Wheeler	In preparation
68.	Cattle heat stress	Development and verification of thermal stress forecasts for cattle in Australia's Rangelands	Tim Cowan, Emily Hinds, Andrew G. Marshall, Matthew C. Wheeler, David Cobon	XII Rangeland Congress 2025

69.	Green Break of Season and Green date	Northern Australia's Green Break of Season (GBOS) dates and their relationship with pasture	Rajashree Naha, Tim Cowan, Matthew C. Wheeler, Jyoteshna Owens, David Cobon, Peter O'Reagain	XII Rangeland Congress 2025
70.	ENSO	Climate impacts of the El Niño–Southern Oscillation on Australia	Andréa S. Taschetto et al. (authors include Sharmila, Cowan, Heidemann, Nguyen, Power)	Nature Reviews Earth & Environment, 7, 103–123, https://doi.org/10.1038/s43017-025-00747-x
71.	Australian rainfall variability	Covariability in large-scale climate modes: implications for Australian precipitation	Boschat, G., S. Power, C. Chung, Z. Gillett, S. Narsey, T. Cowan, A. Purich	Journal of Climate (2026), 39, 997-1014, https://doi.org/10.1175/JCLI-D-24-0651.1
72.	Extension & Adoption	Enhancing climate resilience through the NACP extension service	Andrew Marshall	XII Rangeland Congress 2025
73.	Extension & Adoption	Enhancing climate resilience as a NACP Climate Mate	Emily Hinds	XII Rangeland Congress 2025
74.	Improving Rangeland Grazing Systems	Defining Potential Pathways for Improving the Resilience and Sustainable Development of Rangeland Grazing Systems: Insights from Northern Australia	Thanh Mai, Kathryn Reardon-Smitha, David H Cobon, Thong Nguyen-Huy, Shahbaz Mushtaq	Science of the Total Environment (2025), 978, https://doi.org/10.1016/j.scitotenv.2025.179488
75.	Seamless forecasts	Transforming ensembles towards a target forecast with applications	Taggart R., Griffiths M., Wheeler M.C., Spillman C.M.	QJRM (2025) https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/qj.5051

		for seamless weather to subseasonal forecasting		
76.	Monsoon onset	Why was the official Australian monsoon onset unusually late in 2024/25?	Cowan T., Naha R., Nguyen H., Heidemann H., Narsey S., Wheeler MC, Robinson, C., Lucas C., Marshall AG., and L. Wang	Advances in Atmospheric Sciences (2026). https://doi.org/10.1007/s00376-025-5352-2
77.	Tropical eastern Indian Ocean biases	Persistent model biases in the tropical eastern Indian Ocean region: a seasonal prediction system intercomparison	Hudson, D., Shi, L., Zhou, X., Yin, Y., Wheeler, M.C., Mayer, M., Marzin, C., Kettleborough	Bureau Research Report No. 108
78.	ML evaluation	GraphCast/SF NO ML model performance for S2S forecasts	Cat de Burgh-Day, Debbie Hudson, Harrison Cook, Robin Wedd, Chen Li, Li Shi, Hongyan Zhu, Griff Young	In preparation
79.	High resolution modelling	Modifying CoMorph-A for kilometre-scale resolutions.	S. Lavender, A. Stirling, M. Whitall, A. Lock, S. Smith	Weather and Forecasting, under review
80.	Australian monsoon	The 2024 Asian-Australian Monsoon: Widespread Extremes with Strong Subseasonal Variability and Socioeconomic Impacts	L. Wang, Z. Dong, T. Cowan et al.	Journal of Meteorological Research (2026), 40, 301-318, https://doi.org/10.1007/s13351-026-5262-y
81.	Thermal Stress Projections	How Hot is Too Hot? Projections of Australian	R. Taylor, T. Cowan, S. Perkins-Kirkpatrick	npj Sustainable Agriculture, submitted

		Livestock and Human Thermal Stress under Climate Change		
82.	Climate information services	Building resilience in northern Australian rangeland grazing systems through climate information services.	Wassena, F., Kelly, D., Reardon-Smith, K., Cobon, D., Marshall, A.	In preparation
83.	Cattle chill events	Cattle chill events in northern Australia: observations and predictions	Taylor R., Cowan, T., Hinds, E., Marshall, A.	Weather and Climate Extremes (2026), 51, https://doi.org/10.1016/j.wace.2026.100870
84.	Cattle heat stress forecasts	Creating forecasts of cattle heat stress for Australia: challenges and prototypes	Cowan, T., R. Taylor and S. Maharjan	The Rangeland Journal, under review
85.	Flash Drought	Australian Flash Drought Research: Recent Activities and Ways Forward	Dikshit, A., J.P. Evans, G. Pallavi, D. Cai, T.R. McVicar, A.R. Huete, B. Pradhan, A. Gallant, H. Nguyen, D. Hoffmann, T. J Parker	PLOS Water, submitted
86.	MJO and equatorial wave forecasts	Subseasonal forecasts of the MJO and convectively coupled equatorial waves in ACCESS-S2 and GraphCast: a multi-year analysis	Latos B., H. Nguyen, M.C. Wheeler, C. Li, C. De Burgh-Day, M.E. Hassim, S. Sahany, A. Moise	QJRM, submitted

87.	Tropical cyclone forecasts	Improved tropical cyclone forecasts with CoMorph-A: Physical insights from TC-Kirrily	Zhu, H., D. Hudson, S. Lavender	Bureau of Meteorology Research Report (2026), BRR123, ISBN: 978-1-923469-17-4
88.	Flood case study	The weather and climate driver contributions to the southwest Queensland floods in March 2025	Naha, R., T. Cowan T., M. C. Wheeler, H. Nguyen, S. L. Lavender, A. G. Marshall	In preparation
89.	Livestock chill projections	Future changes in livestock chill across Australia	Taylor, R., T. Cowan	In preparation
90.	Northern Rainfall Onset	Seamless prediction of the Northern Rainfall Onset for northern Australian agriculture	Naha, R., T. Cowan, M. C. Wheeler	In preparation
91.	Humid-Heat Events	Atmospheric drivers of heat stress and heatwave extremes in northern Australia	Jiang, X., R. Naha, T. Cowan	In preparation
92.	Livestock thermal stress	Thriving Through Change: Translating Climate Research into Livestock Productivity Across Northern Australia	Mayne, V., Gaughan, J., Lees, A., Marshall, A., McCosker, K., Cowan, T.	NBRUC Conference Paper, submitted
93.	Livestock thermal stress	Thriving Through Change: Translating Climate Research into	Mayne, V., Gaughan, J., Lees, A., Marshall, A., McCosker, K., Cowan, T.	AAAS Conference Paper, submitted

		Livestock Productivity Across Northern Australia		
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8.2 Appendix 2 – Summary of key outputs

Output Type	Delivered
<i>Monitoring and forecast products</i>	9
<i>Publications (published, submitted and in preparation)</i>	93
<i>Case studies</i>	8
<i>Stakeholders reached</i>	73,344
<i>NACP presentations delivered</i>	>500
<i>MJO forecast map sets (seasonal) delivered to Bureau systems</i>	12

Supporting data for tables and figures is provided separately in accordance with MLA reporting requirements.