BAMS Article

The Northern Australia Climate Program

Overview and Selected Highlights

Sally L. Lavender, Tim Cowan, Matthew Hawcroft, Matthew C. Wheeler, Chelsea Jarvis, David Cobon, Hanh Nguyen, Debra Hudson, S. Sharmila, Andrew G. Marshall, Catherine de Burgh-Day, Sean Milton, Alison Stirling, Oscar Alves, and Harry H. Hendon

ABSTRACT: Since 2017, the Northern Australia Climate Program (NACP) has assisted the pastoral grazing industry to better manage drought risk and climate variability. The NACP funding is sourced from the beef cattle industry, government, and academia, representing the program's broad range of aims and target beneficiaries. The program funds scientists in the United Kingdom and Australia, in addition to extension advisers called "Climate Mates" across a region that supports 15 million head of cattle. Many Climate Mates are employed in the cattle sector and have existing relationships in their communities and capacity to meaningfully engage with the program's intended beneficiaries—red meat producers. The NACP is a prime example of a successful end-to-end program, integrating climate model improvements (research) with tailored forecast products (development), through to direct stakeholder engagement (extension), on-ground application of technologies (adoption), and improvement in industry and community resilience (impact). The climate information needs of stakeholders also feed back to the research and development components, ensuring the scientific research directly addresses end-user requirements. For any scientific research program, ensuring that research output has measurable real-world impact represents a key challenge. This is more difficult in cases where the scientific research is several steps away from the customer's needs. This paper gives an overview of the NACP and research highlights, discussing how the end-to-end framework could be adapted and applied in other regions and industries. It seeks to provide a roadmap for other groups to follow to produce more targeted research with identifiable real-world benefits.

KEYWORDS: Drought; Numerical weather prediction/forecasting; Subseasonal variability; Agriculture; Communications/decision making; Experimental design

https://doi.org/10.1175/BAMS-D-21-0309.1

Corresponding author: Sally Lavender, sally.lavender@usq.edu.au

In final form 15 August 2022

AFFILIATIONS: Lavender and Hawcroft—Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Queensland, Australia, and Met Office, Exeter, United Kingdom; **Cowan and Sharmila**—Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Queensland, and Bureau of Meteorology, Melbourne, Victoria, Australia; **Wheeler, Nguyen, Hudson, de Burgh-Day, and Alves**—Bureau of Meteorology, Melbourne, Victoria, Australia; **Jarvis and Cobon**—Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Queensland, Australia; **Marshall**—Bureau of Meteorology, Hobart, Tasmania, Australia; **Milton and Stirling**—Met Office, Exeter, United Kingdom; **Hendon**—Bureau of Meteorology, and School of Earth, Atmosphere and Environment, Monash University, Melbourne, Victoria, Australia

The Northern Australia Climate Program (NACP) was established based on the economic importance of the northern Australian beef industry and research into the link between the performance of beef cattle production and the use of climate risk information (e.g., Pudmenzky et al. 2017). The need for such a program was highlighted by a prolonged multiyear drought across the region from June 2012 to May 2016. The NACP is led by the Centre for Applied Climate Sciences at the University of Southern Queensland (UniSQ). An initial 6-month planning project (Pudmenzky et al. 2017) funded by Meat and Livestock Australia (MLA; AUD $70,000) helped develop the 4-yr program (NACP phase 2) that was funded by the beef cattle industry (MLA; AUD $4.5 million), government [through the Queensland Government's Drought and Climate Adaptation Program (DCAP); AUD $3.4 million], and academia (UniSQ; AUD $1 million), representing the program's broad range of aims and target beneficiaries. A third and final phase of the NACP extending out to April 2026 has recently been funded.

The main aim of the NACP is to undertake innovative research, development, and extension activities to "improve the capacity of the grazing industry to manage drought and climate risk across northern Australia" (J. McBride 2019, personal communications) with a focus on predictions from subseasonal to multiyear time scales (i.e., not climate projections). The project includes UniSQ employees who are fully embedded in the Australian Bureau of Meteorology (BoM) and the United Kingdom–based Met Office (UKMO). The NACP also currently employs 16 part-time outreach advisers or "Climate Mates" who are regionally scattered across tropical and semiarid northern Australia (north of ~30°S; see Fig. 1), an area of around 5.5 million km^2 that supports close to 15 million head of cattle (Cobon et al. 2021). The majority of Climate Mates either own or manage cattle stations or smaller farms; hence, through their strong community engagement, the Climate Mates help NACP research outcomes to be communicated directly within their region and beyond. This is achieved through on-property visits, climate workshops and regular newsletters that are released by some of the Climate Mates.[1] In turn, information on what is most beneficial to northern producers and pastoralists is fed back to scientists within the research and development (R&D) component of the NACP, through interactive meetings (virtual during the COVID-19 pandemic) or one-on-one engagements. In addition to improving existing collaborations, integrating UniSQ-employed NACP researchers directly into the UKMO and BoM has enabled the project to leverage these institutions' supercomputing resources and intellectual input (e.g., access to world-leading expertise), while in turn providing additional personnel to the institutions.

[1] For example, the Climate Mate located in the Southwest and Central Queensland region releases a monthly newsletter during the summer monsoon season (example of issue 1: https://mcusercontent.com/5a7a7493d421f5f176465db86/files/57a762f0-3dbb-43ef-4627-f584148b7db0/Seasons_Outlooks_with_NACP_Climate_Mate_Vicki_Mayne_Issue_1.pdf).

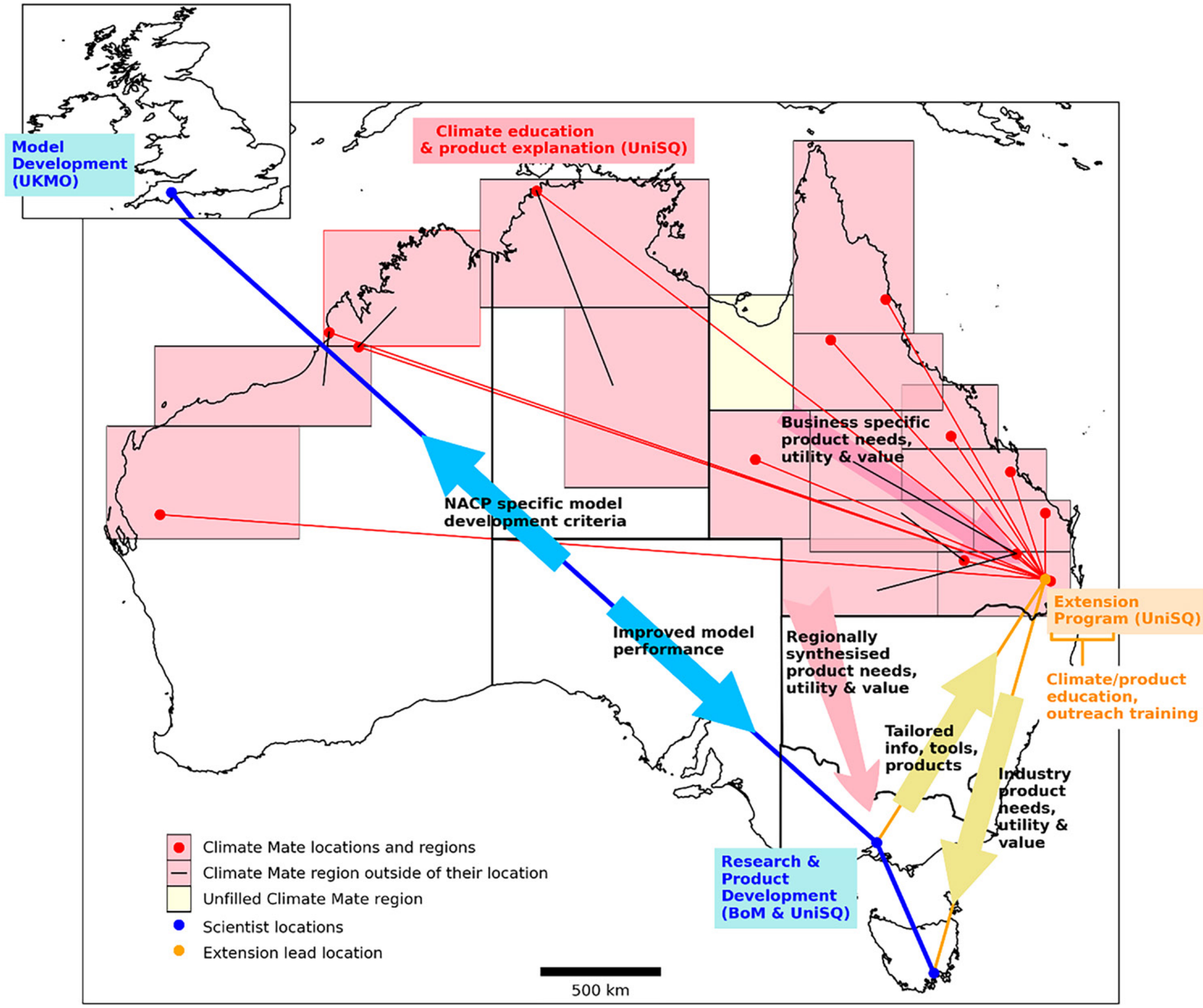

Fig. 1. Map highlighting the different components of the NACP and how they fit together. The blue and orange lines indicate collaboration between UKMO, BoM, and UniSQ scientists. Large arrows represent the flow of information and knowledge between the various institutions. Climate Mates also have direct lines of communication with the NACP scientists and the extension program (displayed as pink arrows).

For pastoralists and their local communities, accurate forecasting of rainfall and drought events is vital for planning and decision-making but more so is the understanding, context, and interpretation of these forecasts. Beef-producing properties in this region can cover vast land areas with average production areas of around 50,000 ha (Brown et al. 2019), typically housing between 1,600 and 5,400 head of cattle (McLean et al. 2014). For the optimal management of these properties, decisions need to be made with a long lead time, particularly for planning on stocking rates and supplementary feed. Shorter lead time forecasts, on the 1–2-week period are also important for planning around the logistics of trucking cattle for export (from the cattle stations to ports), getting fuel onto the property and feed out to the cattle as well as emergency mustering to avoid extreme weather.

This article gives an overview of the different components of the NACP and describes what makes the program so successful in Australia, in a time when climate risk management is a growing area of applied research. This work is motivated by the need to quantify how R&D can facilitate better end-user decisions around managing climate variability and how user feedback can, in turn, drive improvements in dynamical prediction models and forecast tool developments. A program like the NACP could operate in other agricultural regions across the world, and the principles could be readily translated into a program supporting any industry where managing weather and climate information are key to successful decision-making.

Although the NACP is split into different components, discussed in more detail below, they are closely linked (Fig. 1), enabling a clear flow and feedback of information between the scientific institutions, the extension program, and the Climate Mates.

Research

Northern Australia receives ~80% of its annual rainfall in the extended monsoon season between November and April (Sharmila and Hendon 2020), resulting in a limited season for pasture growth (e.g., Brown et al. 2019). Rainfall is highly variable across a range of time scales (Risbey et al. 2009), from intraseasonal bursts and breaks (Lau et al. 2012) to multiyear-to-decadal fluctuations related to low-frequency tropical sea surface temperature (SST) variations (Sharmila and Hendon 2020; Heidemann et al. 2022). Rainfall variability leading to failed wet season starts, protracted droughts, or extreme rainfall events can have a major impact on livestock production (Cobon et al. 2019). Knowledge of the important processes, and the time scales over which they exert influence, directs scientists toward model development activities that improve forecasting over regions of interest at time scales relevant to end users.

The NACP research component is undertaken primarily by BoM- and UKMO-based scientists and focuses on the processes that cause rainfall and drought over northern Australia, and the development and testing of the prediction model for these events. The forecast model used at the BoM exclusively for subseasonal to multiyear prediction is called the Australian Community Climate Earth-System Simulator–Seasonal (ACCESS-S; Hudson et al. 2017), and it is based on the Met Office Unified Model (UM). Developing the model is a multiyear process that involves detailed evaluation of performance at all stages before and after any improvements are made operational (Fig. 2a). Embedding two UniSQ/NACP researchers directly within the UKMO's model development and evaluation teams has helped accelerate model development that specifically focuses on model skill over northern Australia. As the BoM moves toward adopting new UM versions for both numerical weather prediction (NWP) and seasonal forecasting purposes, this work also helps to inform the BoM's development strategy, accelerating pull-through of modeling improvements to the NACP's end users.

One focus of the UKMO work is evaluation of the ability of the latest (and developmental) model configurations to simulate weather and climate phenomena relevant to northern Australia and identifying the physical causes of specific regional biases. Research on UM biases that are important for subseasonal to seasonal predictability of the monsoon have centered on the Indian Ocean Dipole (Figs. 2b,c), particularly the long-standing cold SST bias in the east Indian Ocean. Figure 2c shows the evolution of this bias in the Met Office Global Seasonal Forecasting System version 5 (GloSea5; MacLachlan et al. 2015), which uses the same global coupled science configuration (GC2; Williams et al. 2015) of the UM as ACCESS-S (Hudson et al. 2017). This bias is not unique to the UM, with other coupled models exhibiting similar errors (e.g., Long et al. 2020). The extent and amplitude of this bias has varied as the model physics has been developed over the past few years (e.g., Williams et al. 2015, 2017) and work to understand the nature and sources of this bias is ongoing. Research within the NACP has shown that the bias appears to principally emerge from the atmosphere, with erroneous wind stresses leading to upwelling off Java/Sumatra. Those cold biases then propagate westward, with feedbacks to the atmosphere as the SST errors evolve, amplifying the initial wind errors. The wind biases are evident in atmosphere only simulations, coupled simulations, and seasonal simulations, which further suggests that any errors in the initial conditions in the latter are not the principal cause of the bias.

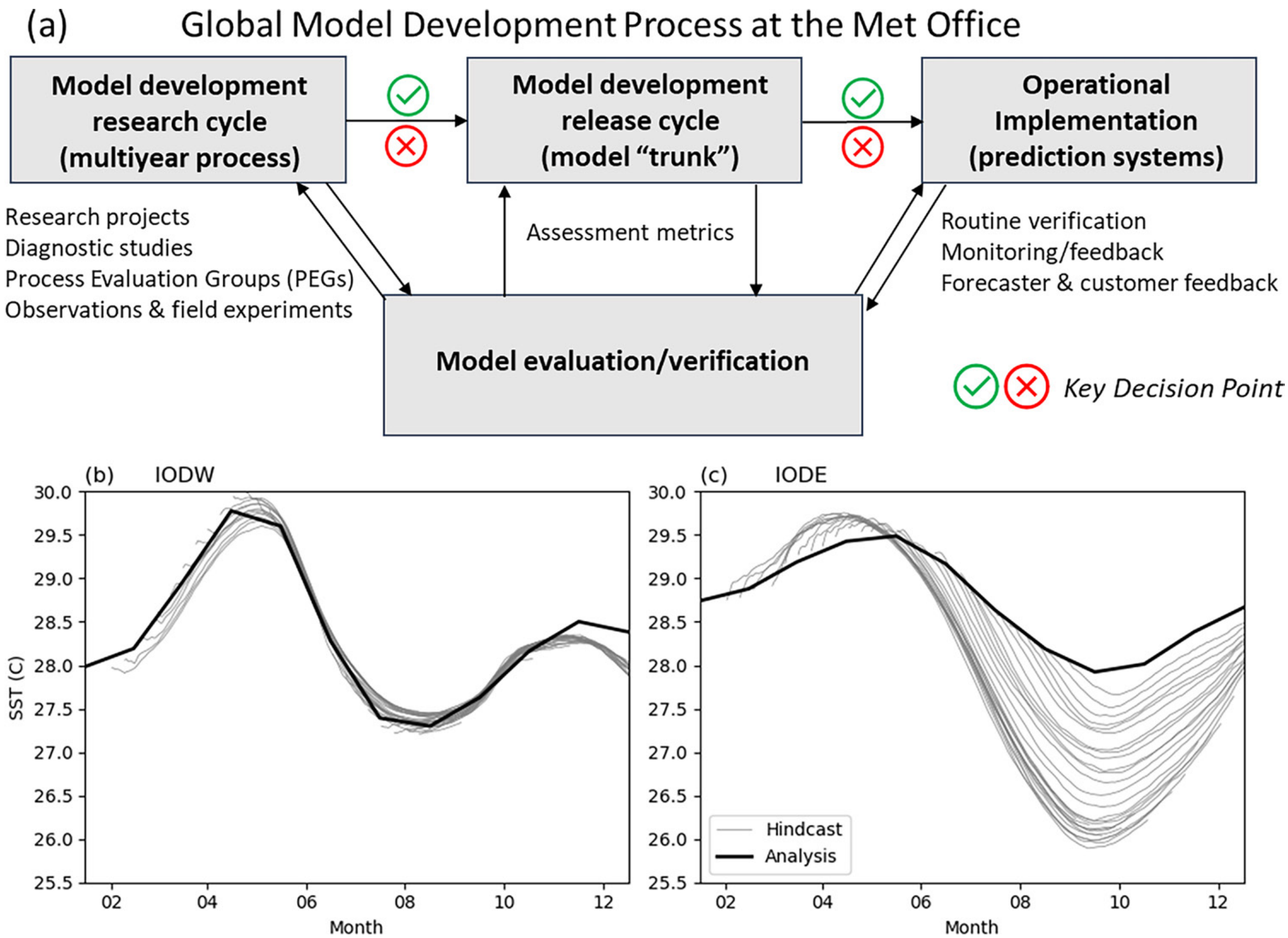

Fig. 2. (a) Overview of the UKMO's model development process, (b) 1993–2016 climatological hindcast SSTs (gray) from Met Office Global Seasonal Forecasting System version 5 (GloSea5; MacLachlan et al. 2015) against a monthly climatology from UM analyses (black) for the western and (c) eastern Indian Ocean, showing the evolution of the bias. Each gray line represents the 216-day hindcast climatology from a given start date (four dates per month between February and August).

A new convective parameterization scheme for the UM, called CoMorph, is under development at the UKMO (Whitall 2021) since the existing scheme lacks much of the structural flexibility required to address systematic biases generated by convection parameterization. Convection scheme improvements will have beneficial impacts for seasonal forecasts over northern Australia. CoMorph has been tested and analyzed extensively as part of the NACP in a wide range of configurations including idealized and single-column models alongside the more common climate and NWP configurations. Results using CoMorph are compared against other model science configurations and observations, with a focus on northern Australia and the surrounding regions as well as important processes such as the Madden–Julian oscillation (MJO).

In addition to strengthening the already existing BoM–UKMO relationship, the NACP has allowed BoM access to CoMorph and simulations from development versions of the model far earlier than would be available through accessing the periodic official science configuration releases from the UKMO (which do not yet include CoMorph). This has included porting of the latest UM and coupled model science configurations to the BoM, paving the way for their use in the seasonal forecasting system. It is now possible for the BoM to run experiments with

CoMorph in the coupled model configuration, a process that has not yet been completed at the UKMO. This not only benefits Australian farmers and pastoralists, but these results can be fed back into the UKMO development and decision-making process.

In February 2019, extreme flooding across northeast Australia and the associated cold temperatures and wind chill conditions significantly impacted the cattle industry across the Gulf of Carpentaria coast drainage basin (Cowan et al. 2022a). The dynamics and nature of the event in the observational and historical climate context were documented by NACP scientists at the BoM with analysis of the ability of several international subseasonal to seasonal (S2S) prediction systems to forecast the flood event (Cowan et al. 2019). The study concluded that the S2S systems underestimated the magnitude of the extreme rainfall event in their lead week-1 forecasts, although around ten S2S systems predicted twice the climatological probability of extreme chill conditions (Cowan et al. 2022a). This motivated a more detailed UM study to understand the benefits of multiweek ensemble forecasting for extreme, and damaging, events of this nature (Hawcroft et al. 2021). This provides an important test bed for future significant events over northern Australia and demonstrates the benefits of both coupled and ensemble forecasting for such events. The NACP studies also showed the critical gap in multiweek forecasting space. In June 2019, the BoM introduced multiweek forecasts to their seasonal climate outlooks, with a particular focus on rainfall and temperature extremes.

Research on drought has been on two significantly different time scales, flash droughts (Nguyen et al. 2019, 2020, 2021), which rapidly intensify over a few weeks (results discussed in the next section), and multiyear droughts (Sharmila and Hendon 2020). Within the NACP, Sharmila and Hendon (2020) evaluated underlying mechanisms of multiyear wet/dry conditions over Northern Australia, highlighting the importance of both local (wind–evaporation–rainfall feedback combined with subsurface soil memory) and remote [low-frequency El Niño–Southern Oscillation (ENSO)-induced tropical Pacific SST variability] influences across the region. Using multiyear hindcast ensembles, the NACP scientists have identified long-range predictable aspects of ENSO variability relevant to northern Australia, whereby ENSO can be skillfully predicted out to at least 18 months in hindcasts initialized in November (Sharmila et al. 2022). Back-to-back El Niño events that typically lead to a period of prolonged drought are also found to be highly predictable, despite hindcasts underestimating the magnitude of equatorial Pacific surface conditions. This work underpins the basis for BoM's intention to extend seasonal forecasting toward an operational 2-yr ENSO/climate prediction framework (Bureau of Meteorology 2021).

The research component of the project feeds directly into the development of products for use by end users, as described in the following section, as well as ultimately helping to improve model performance over the region. In turn the development and extension components help to guide the direction of research which has most relevance to the project.

Development

Helping northern Australian pastoralists make better-informed decisions is the driving motivation behind the design and production of innovative prototype forecast products in the NACP. Here, we summarize the flash drought and rainfall burst potential products that were specifically developed within the NACP and detail the process whereby these products were created and improved upon with direct input from end users.

Flash drought. The motivation behind the flash drought product, which describes the rapid evolution and intensification into drought over a few weeks, arose from discussions with a sheep farmer in southern Queensland, who experienced such an event in early

2018 (Nguyen et al. 2019). Tropical northern Australia is a flash drought hotspot, particularly around the time of the summer monsoon commencement (Christian et al. 2021). The flash drought prototype product development stemmed from close collaborations between BoM researchers and U.S. drought experts at the University of Wisconsin–Madison, the latter having used the evaporative stress index (ESI) in demonstrating dry conditions in the U.S. Drought Monitor maps (Otkin et al. 2018b).

The ESI is defined as the standardized anomaly of the ratio of actual evapotranspiration to potential evapotranspiration (Nguyen et al. 2019, and references therein). As a flash drought develops, the ESI drops rapidly as actual evapotranspiration decreases and potential evapotranspiration increases (Otkin et al. 2018a). Strongly linked to rainfall variability and warm season temperatures (Nguyen et al. 2020), the ESI can be used to explain the impact of drought-inducing climate modes across Australia (Nguyen et al. 2021). The ESI has been shown to be strongly related to soil moisture conditions in the upper-level (7–28 cm) root zone across Australia in the austral spring and summer seasons, and, as it includes atmospheric demand in its formulation, has been shown to be useful for monitoring developing flash droughts (Parker et al. 2021).

Three prototype flash drought products were developed from the ESI (Nguyen et al. 2022, manuscript submitted to *J. Hydrometeor.*):

- δESI: Standardized difference in ESI over 2 weeks
- Rapid change index (RCI): Set to 1 when the δESI drops to below the 20th percentile
- Flash drought index (FDI): Set to 1 when RCI is 1 for at least 2 weeks and ESI < –1 at the end of the 2 weeks

A flash drought then is determined when the FDI remains 1 for at least 4 consecutive weeks. An example of the three forecast products, for a 4-week prediction from ACCESS-S1,[2] initialized on 13 September 2021, is shown in Fig. 3. The forecast indicates negative ESI values approaching –2 over the southwest of Australia, and slightly weaker values in the far southeast, along the southern Great Dividing Range. Despite the resultant RCI and FDI values indicating the potential for dry conditions, only the southwest displays FDI values > 28 days (i.e., the potential for flash drought). At the time of writing, the flash drought product is unavailable as a forecast product; however, there are plans in place to make this a prototype product.

[2] This is version 1 of the ACCESS-S subseasonal to seasonal prediction system, which became operational in August 2018. As of October 2021, the BoM has been providing forecasts from version 2 (ACCESS-S2).

Rainfall burst product. Northern Australian primary producers rely heavily upon knowing when meaningful rainfall will occur across their region during the summer monsoon. Relating to the availability of new pasture, the first rain "burst" is sometimes called the green break of the season (Balston and English 2009). In developing a wet season break forecast product using ACCESS-S1 (Hudson et al. 2017), the NACP scientists needed to create a product that was both simple to understand and applicable across northern Australia, with its highly variable climate and different soil types.

Consultation with the Climate Mates led to a rainfall burst event definition stating that accumulated rain amounts (e.g., 20, 30, 50, 70 mm) over 3 consecutive days are required for an event to be deemed a burst. Initially, two products were created:

1) rainfall burst potential: the probability of a rainfall burst *starting* during the forecast period (e.g., weeks 1–3 and fortnights 1–3); and
2) number of burst days: ensemble median of burst days within the forecast period.

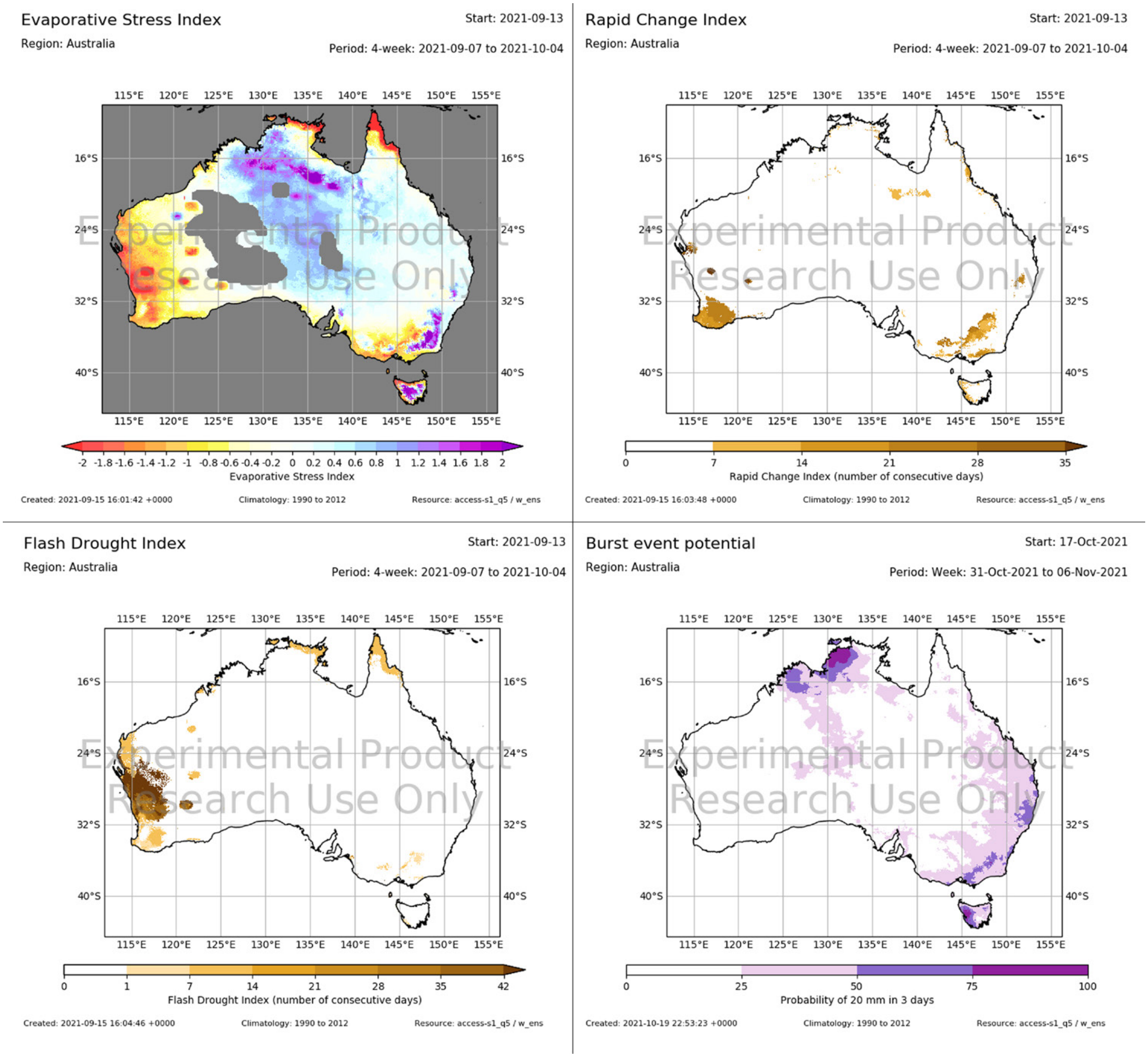

Fig. 3. Example ACCESS-S1 prototype forecast products, which include (top left) evaporative stress index (ESI), (top right) rapid change index (RCI), (bottom left) flash drought index (FDI), and (bottom right) rainfall burst event potential. Specific details on the forecast dates and units are given within the panels.

Further discussions with Climate Mates aided scientists in discontinuing product 2, with feedback indicating there was confusion over distinguishing a burst event and burst day. For product 1, dialogue with the Climate Mates proved instructive for finalizing color schemes, appropriate thresholds and relaxing the minimum daily amount condition. The final prototype burst potential product (see example in Fig. 3) was presented to the general public at a major national beef cattle conference in early May 2020, where it received local press media coverage.[3] Following widespread feedback from producers and support from the BoM's Forewarned is Forearmed project (Hayman and Hudson 2021), the rainfall burst potential product was selected to become operational (Cowan et al. 2022b) and released in May 2022 as a forecast "Chance of 3-day totals"

[3] www.graincentral.com/weather/beef-2021-nacps-burst-to-forecast-meaningful-rain/

(www.bom.gov.au/climate/outlooks/#/rainfall/burst/15/weekly/0). The formal operational product includes different thresholds, particularly on the lower tail (e.g., 15 mm; appropriate for southern wheat producers), and thresholds that better align with older generational graziers who use imperial units (e.g., 1–3 in.; A. Hawksford 2021, personal communications). Planning ahead, future development will be centered on developing a prototype product more closely tied with actual or modeled pasture responsiveness to early wet season rainfall (e.g., green dates), which is strongly tied to flash drought occurrence.

Extension

The Climate Mates link researchers and end users, facilitating the uptake by producers of the NACP's research and development outputs as well as providing relevant feedback from producers to researchers (Cobon et al. 2021). Climate Mates are employed 0.2 FTE by UniSQ. Around half of the Climate Mates are red meat producers and the other half work for natural resource management (NRM; https://nrmregionsaustralia.com.au/) organizations or have an agricultural consultancy background. The Climate Mates were hired based on their living in a priority region, local knowledge of the red meat industry, industry networks, and communication skills. Training in weather, climate, and forecasting was provided by BoM/UniSQ/UKMO staff to ensure a thorough understanding by the Climate Mates of relevant topics and knowledge on how to correctly interpret a forecast and where to find this information online. In addition to guidance from the BoM/UKMO, the Climate Mates are also supported by a full-time NACP climatologist, specializing in applied climate science. Regular virtual meetings and annual in-person NACP meetings assist in keeping the Climate Mates up to date on the latest science, and strengthen the bonds and promote camaraderie between the NACP's R&D, and extension teams.

Information is communicated to red meat producers and the related supply chain by the Climate Mates, mainly through face-to-face interactions, such as property visits, workshops, and seminars. Due to COVID-19, the NACP developed an online mini climate course for those unable to attend in-person gatherings and webinars have become an important avenue to connect with producers. Half-day NACP workshops review relevant climate drivers, such as ENSO, how to interpret a seasonal forecast, where to find climate/forecast information online, and how to incorporate this information into a property management plan. BoM/UniSQ employees are encouraged to present at these events along with the NACP climatologist and the local Climate Mates (e.g., Marshall 2021). This primarily allows the NACP researchers to learn firsthand the needs of producers, which is a critical component to improving and targeting research and development (Hunt et al. 2011). Additionally, these interactions allow producers to "put a face" to researchers at the BoM, which leads to improved confidence and trust in the BoM and their forecasts.

Monitoring/evaluation

The extension program adapted a three-step approach to user engagement (Hewitt et al. 2017) and delivered a four-step approach (Fig. 4) by providing a mix of passive and active climate engagement services to producers with goals to meet the following categories: 1) improve awareness; 2) improve knowledge aspiration, skills, and attitude (KASA); 3) change management practice; and 4) measure impact and leave a legacy. Websites, newsletters, and social media are examples of passive engagement that provide information about climate that contributes to improved awareness; face-to-face activities such as workshops, multitopic days, and field days are interactive and improve KASA; and one-on-one contact is active engagement that builds relationships, and confidence that drives practice change and builds a level of trust between Climate Mates and producers to share the business data required to measure impact.

Challenging targets were set for categories 1, 2, and 3 at the outset and metrics recorded throughout the NACP to demonstrate their achievement. Of a total client base of ~9,000 red meat producers in northern Australia, targets were set of 5,500, 420, and 150 for

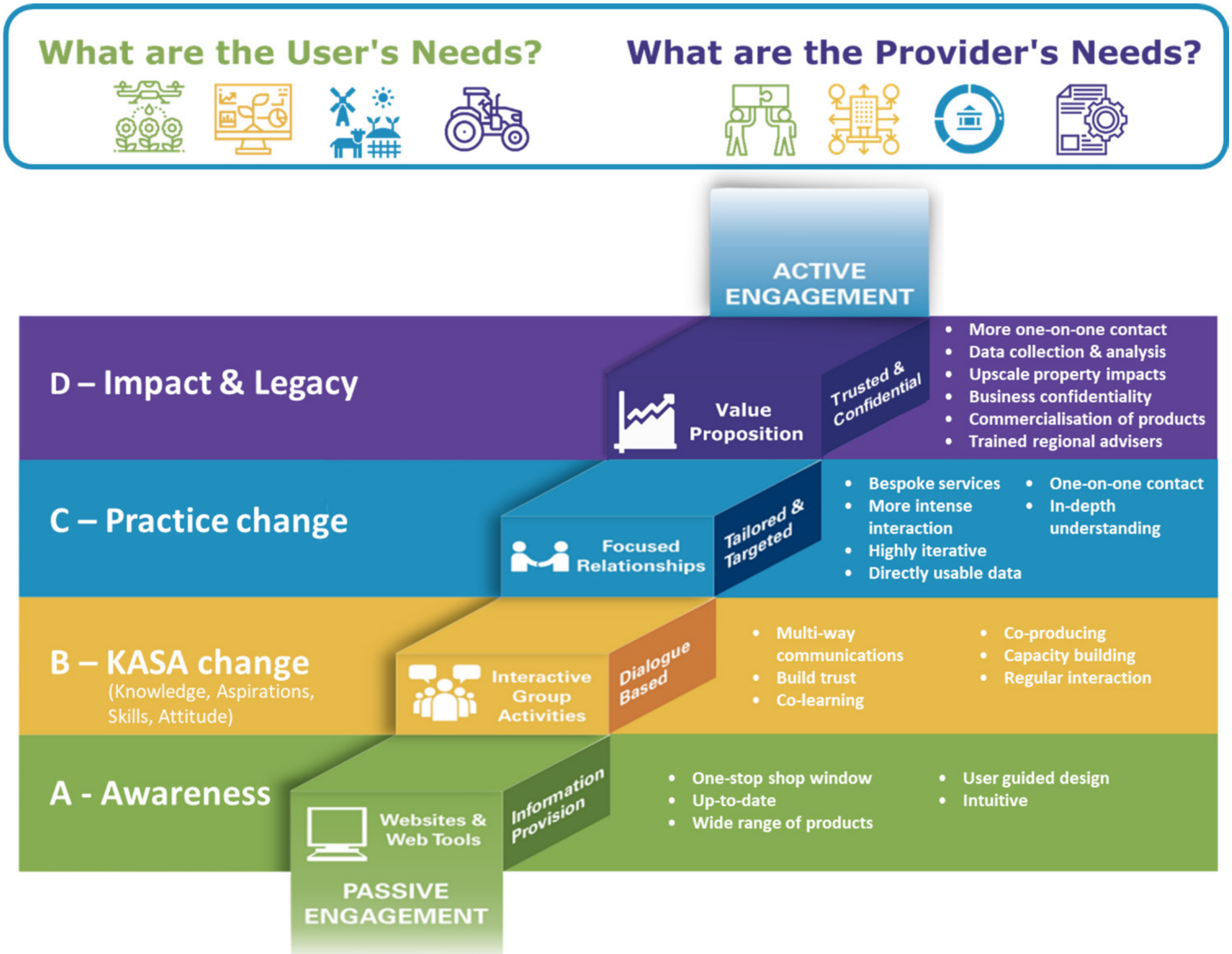

Fig. 4. Schematic of four broad categories of engagement between users (e.g., primary producers) and funding providers (e.g., MLA, DCAP, UniSQ) of climate services. Adapted with permission from Hewitt et al. (2017).

categories 1, 2, and 3, respectively. The criteria needed to meet these targets is provided in Cobon et al. (2021). To meet the targets, the team delivered 77 workshops (including 40 specifically on managing climate variability); 130 presentations at field days, multitopic days and forums; 117 property visits; and 16 webinars—the total number of attendees was 5,133. Categories 1 and 2 targets were significantly exceeded, and category 3 targets were achieved. Passive engagement (category 1) was relatively easy and resource cheap to deliver whereas active engagement (category 3) required repeated follow-up with producers and was time consuming and resource intensive. In terms of the workshops, 68% were delivered in Queensland, perhaps reflecting the lack of interstate travel by the NACP researchers during the extended lockdown periods during the COVID-19 pandemic (i.e., states and territories locked down borders). In these workshops, over 61% of the workshop attendees ($N = 419$) were cattle (and other livestock) producers, but these statistics are likely skewed by the numbers from Queensland. Further research into the attendee breakdown and products of most interest to stakeholders may be pursued in the extension project (e.g., desire for cattle heat load or chill indices).

Providers of funds are increasingly asking for projects to demonstrate on-ground impact (category 4) so identifying practice change and collecting data on benefits and costs associated with a changed management decision can provide a value proposition. This requires intensive one-on-one discussions with the producer to gather economic data that are often considered private and personal. The team collected data from nine producers who used the NACP products or advice from Climate Mates. Practice changes resulting from NACP included early weaning, calving set to green date, selling cattle late, pasture establishment in two regions, early mustering for live export, moving cattle to avoid heat stress and flooding. The average on-property economic benefit was AUD $22 per head of cattle, consistent with bioeconomic modeling studies of other decisions conducted in northern Australia (An-Vo et al. 2019; Cobon et al. 2020; Darbyshire et al. 2020). Regarding legacy, the Climate Mates are located throughout northern Australia and because many are producers, the climate knowledge, and contacts they have acquired will benefit them and other producers in the region in the future. Developing commercial climate courses delivered by Climate Mates or accredited trainers is another project legacy sort after by providers.

The monitoring and evaluation component provides vital details on how well the project is working in different areas and any shortcomings. These are fed back to the RD&E components so the products and methods can be adjusted as required.

Summary

This paper has broadly summarized the different components of the NACP. The importance of an end-to-end program, integrating climate model improvements (research) with tailored forecast products (development), through to direct engagement with stakeholders (extension), on-ground application of technologies (adoption), and improvement in industry and community resilience (impact) is key to the success of the NACP. These principles could be readily translated into a program in other regions of the globe and supporting any industry where managing weather and climate information are key to successful decision-making.

The inclusion of the NACP Climate Mates is crucial, providing the important link between the R&D components and the producers, allowing for information to be directed to those who need it most. In turn, Climate Mates provide a route to communicate back to the scientists, resulting in tailored modifications to BoM products based on this vital feedback from those who use them.

An innovative project such as this does not come without its own challenges, some of which may be beneficial to the reader when considering development of similar projects. From a researcher perspective it is important to understand that those in the meat industry make no strong distinction between the “weather” and “climate” and have multiple decisions they make that can be influenced by all time scales of forecasts from short-term weather forecasts out to multiyear. Simply providing and communicating forecasts is not well-received and it is important to explain why the forecast is saying what it does, which often involves explanations of the weather and climate drivers like ENSO and the MJO. From an extension and monitoring/evaluation perspective, the training methods need to be simple and tailored toward methods that provide clear pathways to practice change such as how to use weather climate information in everyday decision-making. Identifying agreed methods to demonstrate national-scale economic impact has been a challenge. The schematic in Fig. 4 has been a very useful tool in M&E and demonstrating increase in awareness and knowledge, and practice change. And, of course, recruitment of the right people who can communicate effectively across the full RD&E program is vitally important.

There are proven benefits and financial gains with the NACP achieving a change in practice by successfully incorporating climate information and tools into management decisions that result in improved economic, environmental, and/or social outcomes. In addition, the long-term benefits of the model development process and multiyear prediction improvements are yet to be realized due to the time scales involved (Fig. 2a), with investment in fundamental research able to yield gains beyond the project's lifetime. As of April 2022, a 4-yr extension to the NACP has been finalized.

Acknowledgments. More details of NACP can be found at https://nacp.org.au. The NACP is funded by Meat and Livestock Australia, the Queensland Government through the Drought and Climate Adaptation Program, and the University of Southern Queensland. We are grateful to Christine Chung and Ghyslaine Boschat for providing important feedback on the manuscript. We also thank Nina Usher for making modifications to Fig. 4. We thank John McBride for his input to the R&D components of the project and initially suggesting this overview paper.

Data availability statement. GloSea5 data (Fig. 2) were provided by the Met Office and can be accessed from the S2S database hosted at ECMWF. Hindcast data from ACCESS-S1 are available from TC upon reasonable request.

References

An-Vo, D.-A., K. Reardon-Smith, S. Mushtaq, D. Cobon, S. Kodur, and R. Stone, 2019: Value of seasonal climate forecasts in reducing economic losses for grazing enterprises: Charters Towers case study. *Rangeland J.*, **41**, 165–175, https://doi.org/10.1071/RJ18004.

Balston, J., and B. English, 2009: Defining and predicting the "break of the season" for north-east Queensland grazing areas. *Rangeland J.*, **31**, 151–159, https://doi.org/10.1071/RJ08054.

Brown, J. N., A. Ash, N. MacLeod, and P. McIntosh, 2019: Diagnosing the weather and climate features that influence pasture growth in northern Australia. *Climate Risk Manage.*, **24**, 1–12, https://doi.org/10.1016/j.crm.2019.01.003.

Bureau of Meteorology, 2021: Science and innovation. Bureau of Meteorology 2020–21 Annual Rep., 80 pp., www.transparency.gov.au/annual-reports/bureau-meteorology/reporting-year/2020-21-10.

Christian, J. I., J. B. Basara, E. D. Hunt, J. A. Otkin, J. C. Furtado, V. Mishra, X. Xiao, and R. M. Randall, 2021: Global distribution, trends, and drivers of flash drought occurrence. *Nat. Commun.*, **12**, 6330, https://doi.org/10.1038/s41467-021-26692-z.

Cobon, D. H., L. Kouadio, S. Mushtaq, C. Jarvis, J. Carter, G. Stone, and P. Davis, 2019: Evaluating the shifts in rainfall and pasture-growth variabilities across the pastoral zone of Australia during 1910–2010. *Crop Pasture Sci.*, **70**, 634–647, https://doi.org/10.1071/CP18482.

——, R. Darbyshire, J. Crean, S. Kodur, M. Simpson, and C. Jarvis, 2020: Valuing seasonal climate forecasts in the northern Australia beef industry. *Wea. Climate Soc.*, **12**, 3–14, https://doi.org/10.1175/WCAS-D-19-0018.1.

——, C. Jarvis, K. Reardon-Smith, L. Guillory, C. Pudmenzky, T. Nguyen-Huy, S. Mushtaq, and R. Stone, 2021: Northern Australia Climate Program: Supporting adaptation in rangeland grazing systems through more targeted climate forecasts, improved drought information and an innovative extension program. *Rangeland J.*, **43**, 87–100, https://doi.org/10.1071/RJ20074.

Cowan, T., and Coauthors, 2019: Forecasting the extreme rainfall, low temperatures, and strong winds associated with the northern Queensland floods of February 2019. *Wea. Climate Extremes*, **26**, 100232, https://doi.org/10.1016/j.wace.2019.100232.

——, M. C. Wheeler, C. de Burgh-Day, H. Nguyen, and D. Cobon, 2022a: Multi-week prediction of livestock chill conditions associated with the northwest Queensland floods of February 2019. *Sci. Rep.*, **12**, 5907, https://doi.org/10.1038/s41598-022-09666-z.

——, ——, S. Sharmila, S. Narsey, and C. de Burgh-Day, 2022b: Forecasting northern Australian summer rainfall bursts using a seasonal prediction system. *Wea. Forecasting*, **37**, 23–44, https://doi.org/10.1175/WAF-D-21-0046.1.

Darbyshire, R., and Coauthors, 2020: Insights into the value of seasonal climate forecasts to agriculture. *Aust. J. Agric. Resour. Econ.*, **64**, 1034–1058, https://doi.org/10.1111/1467-8489.12389.

Hawcroft, M., S. Lavender, D. Copsey, S. Milton, J. Rodríguez, W. Tennant, S. Webster, and T. Cowan, 2021: The benefits of ensemble prediction for forecasting an extreme event: The Queensland floods of February 2019. *Mon. Wea. Rev.*, **149**, 2391–2408, https://doi.org/10.1175/MWR-D-20-0330.1.

Hayman, P., and D. Hudson, 2021: Forewarned is forearmed—Exploring the value of new forecast products from the BOM to enable more informed decisions on profit and risk on grain farms. Grains Research and Development Corporation Rural R&D for Profit Program Rep., 11 pp., https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2021/05/forewarned-is-forearmed-exploring-the-value-of-new-forecast-products-from-the-bom-to-enable-more-informed-decisions-on-profit-and-risk-on-grain-farms.

Heidemann, H., J. Ribbe, T. Cowan, B. J. Henley, C. Pudmenzky, R. Stone, and D. H. Cobon, 2022: The influence of interannual and decadal Indo-Pacific sea surface temperature variability on Australian monsoon rainfall. *J. Climate*, **35**, 425–444, https://doi.org/10.1175/JCLI-D-21-0264.1.

Hewitt, C., R. Stone, and A. Tait, 2017: Improving the use of climate information in decision-making. *Nat. Climate Change*, **7**, 614–616, https://doi.org/10.1038/nclimate3378.

Hudson, D., and Coauthors, 2017: ACCESS-S1: The new Bureau of Meteorology multi-week to seasonal prediction system. *J. South. Hemisphere Earth Syst. Sci.*, **67**, 132–159, https://doi.org/10.1071/ES17009.

Hunt, W., F. Vanclay, C. Birch, J. Coutts, N. Flittner, and B. Williams, 2011: Agricultural extension: Building capacity and resilience in rural industries and communities. *Rural Soc.*, **20**, 112–127, https://doi.org/10.5172/rsj.20.2.112.

Lau, W. K. M., D. E. Waliser, M. C. Wheeler, and J. L. McBride, 2012: Australasian monsoon. *Intraseasonal Variability in the Atmosphere-Ocean Climate System*, 2nd ed. W. K. M. Lau and D. E. Waliser, Eds., Springer Praxis Books, Springer, 147–198, https://doi.org/10.1007/978-3-642-13914-7_5.

Long, S., G. Li, K. Hu, and J. Ying, 2020: Origins of the IOD-like biases in CMIP multimodel ensembles: The atmospheric component and ocean–atmosphere coupling. *J. Climate*, **33**, 10 437–10 453, https://doi.org/10.1175/JCLI-D-20-0459.1.

MacLachlan, C., and Coauthors, 2015: Global Seasonal forecast system version 5 (GloSea5): A high-resolution seasonal forecast system. *Quart. J. Roy. Meteor. Soc.*, **141**, 1072–1084, https://doi.org/10.1002/qj.2396.

Marshall, A. G., 2021: Lessons learned in outback Western Australia. *Bull. Aust. Meteor. Oceanogr. Soc.*, **34**, 22–24.

McLean, I., P. Holmes, and D. Counsell, 2014: The Northern Beef Report: 2013 northern beef situation analysis. Meat and Livestock Australia Rep., 154 pp.

Nguyen, H., M. C. Wheeler, J. A. Otkin, T. Cowan, A. Frost, and R. Stone, 2019: Using the evaporative stress index to monitor flash drought in Australia. *Environ. Res. Lett.*, **14**, 064016, https://doi.org/10.1088/1748-9326/ab2103.

——, J. A. Otkin, M. C. Wheeler, P. Hope, B. Trewin, and C. Pudmenzky, 2020: Climatology and variability of the evaporative stress index and its suitability as a tool to monitor Australian drought. *J. Hydrometeor.*, **21**, 2309–2324, https://doi.org/10.1175/JHM-D-20-0042.1.

——, M. C. Wheeler, H. H. Hendon, E.-P. Lim, and J. A. Otkin, 2021: The 2019 flash droughts in subtropical eastern Australia and their association with large-scale climate drivers. *Wea. Climate Extremes*, **32**, 100321, https://doi.org/10.1016/j.wace.2021.100321.

Otkin, J. A., M. Svoboda, E. D. Hunt, T. W. Ford, M. C. Anderson, C. Hain, and J. B. Basara, 2018a: Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bull. Amer. Meteor. Soc.*, **99**, 911–919, https://doi.org/10.1175/BAMS-D-17-0149.1.

——, T. Haigh, A. Mucia, M. C. Anderson, and C. Hain, 2018b: Comparison of agricultural stakeholder survey results and drought monitoring datasets during the 2016 U.S. northern plains flash drought. *Wea. Climate Soc.*, **10**, 867–883, https://doi.org/10.1175/WCAS-D-18-0051.1.

Parker, T., A. Gallant, M. Hobbins, and D. Hoffmann, 2021: Flash drought in Australia and its relationship to evaporative demand. *Environ. Res. Lett.*, **16**, 064033, https://doi.org/10.1088/1748-9326/abfe2c.

Pudmenzky, C., D. H. Cobon, S. Mushtaq, and R. Stone, 2017: Northern Australia Climate Project Phase 1. Meat and Livestock Australia Final Rep., 31 pp., www.nacp.org.au/static/pdf/Northern%20Australia%20Climate%20Project%20Phase%201.pdf.

Risbey, J. S., M. J. Pook, P. C. McIntosh, M. C. Wheeler, and H. H. Hendon, 2009: On the remote drivers of rainfall variability in Australia. *Mon. Wea. Rev.*, **137**, 3233–3253, https://doi.org/10.1175/2009MWR2861.1.

Sharmila, S., and H. H. Hendon, 2020: Mechanisms of multiyear variations of northern Australia wet-season rainfall. *Sci. Rep.*, **10**, 5086, https://doi.org/10.1038/s41598-020-61482-5.

——, ——, O. Alves, A. Weisheimer, and M. Balmaseda, 2022: Contrasting El Niño–La Niña Predictability and Prediction Skill in 2-Year Reforecasts of the Twentieth Century. *J. Climate*, https://doi.org/10.1175/JCLI-D-22-0028.1, in press.

Whitall, M., 2021: The CoMorph convection scheme. Unified Model Documentation Paper 43, 79 pp.

Williams, K. D., and Coauthors, 2015: The Met Office Global Coupled model 2.0 (GC2) configuration. *Geosci. Model Dev.*, **8**, 1509–1524, https://doi.org/10.5194/gmd-8-1509-2015.

——, and Coauthors, 2017: The Met Office Global Coupled model 3.0 and 3.1 (GC3.0 and GC3.1) configurations. *J. Adv. Model. Earth Syst.*, **10**, 357–380, https://doi.org/10.1002/2017MS001115.