Final report

Northern Australia Climate Program

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Prepared by: David Cobon and the NACP Team
University of Southern Queensland

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Abstract

Red meat producers in northern Australia have concerns regarding climate prediction: low and variable forecast skill; low relevance of existing forecast systems; lack of understanding on how to use climate resources; lack of support from climate experts; and lack of proof of value in using climate forecasts in decision-making.

The Northern Australia Climate Program was developed to overcome these barriers to adoption by improving the accuracy of the climate model, producing new and improved climate forecasts at multiple timescales; producing new and locally relevant decision (and discussion) support tools; and providing a trusted extension service to help producers integrate climate prediction technologies into decision making.

The research has made significant improvements to the climate model.

The development and extension have delivered sort-after products, a website, producer and adviser digital climate training modules, climate workbooks, regional climate guides and weekly and monthly climate outlooks.

Executive summary

Red meat producers in northern Australia have concerns regarding climate prediction: low and variable forecast skill; low relevance of existing forecast systems; lack of understanding on how to use climate resources; lack of support from climate experts; and lack of proof of value in using climate forecasts in decision-making.

The Northern Australia Climate Program (NACP) was developed to overcome these barriers to adoption by improving the accuracy of the climate model, producing new and improved climate forecasts at multiple timescales; producing new and locally relevant decision (and discussion) support tools; and providing a trusted extension service to help producers integrate climate prediction technologies into decision making.

The research has made significant improvements to the climate model and the work on multi-year drought indicates useful prediction skill is likely out to 18 months.

The development and extension have delivered sought-after products including the Madden Julian Oscillation forecast, Northern Rainfall Onset, Drought Monitor, Drought Outlook, Green Date, Rainfall Burst, Chill Index, and a prototype forecast of Flash Drought. Other products include a website, producer and adviser digital climate training modules, climate workbooks, regional climate guides and weekly and monthly climate outlooks.

The extension has appointed and trained 22 Climate Mates located across northern Australia that have made considerable progress to improve climate knowledge of producers and advisers and helped them integrate this knowledge into decision making. The value of this to the industry is between $12 to $21 million per year. The extra value of research through increased accuracy of climate prediction at multiple timescales has not been evaluated.

Two recent independent reviews found the research to be world class, producing significant and important scientific achievements, and the development and extension to be well integrated and delivering products and an extension service of quality, value and impact. These reviews recommended another 4-year phase of funding in research, development and extension to continue to build momentum and provide a lasting legacy.

The project has either prepared, submitted or published 49 scientific publications in Q1/Q2 journals.

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1. Model convection improvements at the BoM

Oscar Alves, Catherine de Burgh Day
Bureau of Meteorology, Melbourne, Victoria, Australia

1.1 Background

The Bureau of Meteorology (BoM) uses versions of the UK Met Office (UKMO) model for forecasting across a range of timescales from weather forecasting to seasonal forecasting. The UKMO coupled model GC2 is the main modelling system used for multi-week and seasonal prediction as part of ACCESS-S2. As part of NACP two USQ/NACP staff were seconded to the UKMO to accelerate model development that specifically focusses on model skill over northern Australia. The focus of this work was to assist and bring forward work on a new convection scheme (CoMorph), to develop a suite of evaluation tools relevant to Northern Australia, and to carry out evaluations on new versions of the UKMO coupled models (e.g. GC3, G4 and components being build for GC5). The long-term objective was to ensure that future versions of the UKMO coupled model (GC5 onwards) would perform better over Australia.

The work at UKMO mainly focused on developing components of the models and testing how well models simulated different weather and climate processes (eg El Nino). More generally (beyond NACP) UKMO undertake a significant evaluation of how each new model performs for weather forecasting and climate change projections.

The focus of the NACP model development work at BoM is to develop a testing framework to assess how each new model version performs in multi-week and/or seasonal prediction configuration. The aim is to import different releases of the UKMO coupled model and conduct a series of case studies on multi-week and seasonal time scales. The setting up of the technical framework to enable this to happen and carrying out initial case studies represented a substantial amount of work.

The tools developed at the UKMO and BoM have also been used to contribute to understanding causes of skill degradation over northern Australia such as biases in the Indian Ocean, through activities such as the Indo-Pacific Priority Evaluation Group (PEG). PEGs are joint research initiatives coordinated through the UKMO Partnership, with the Indo-Pacific PEG being jointly led by staff at the BoM, UKMO and at the European Centre for Medium Range Weather Forecasting (ECMWF). The Indo-Pacific specifically focused on understanding model biases in the Indian Ocean, that are believed to be the biggest limiter to increased forecast accuracy.

1.2 Objectives

The objective of this component is to build the capacity in Australia to contribute to the development of, and to test and evaluate particularly in multi-week/seasonal prediction mode, new coupled model improvements of the joint UKMO/BOM GC* series of coupled models, and to contribute to initiatives such as the Indo-Pacific PEG. This is done with a focus on reducing model errors and biases, and improving forecast accuracy over Northern Australia. This is to ensure that UKMO/BOM GC* versions used in future upgrades of ACCESS-S show greater accuracy than would be the case otherwise, and therefore provide NACP stakeholders and customers with future ACCESS-S forecasts with superior multi-week and seasonal forecast accuracy.

1.3 Methodology

1.3.1 UKMO Global Coupled model version 4

The UKMO Global Coupled model version 4 (GC4) is the most recent (as of February 2022) frozen release of the UKMO coupled modelling system. For comparison, the current operational seasonal model version at the Bureau (ACCESS-S2) is based on GC2. GC4 is comprised of Global Atmosphere version 8.0 (GA8; also called the UM), Global Land version 9.0 (GL9; based on JULES), Global Ocean version 6.0 (GO6; based on NEMO), and Global Sea Ice version 8.1 (GSI8.1, based on CICE), and was frozen in March 2020.

The relationship between different model components, scientific configurations and suite configurations can be confusing. To aid in the reader's understanding, a diagrammatic representation of the relationship between ACCESS-S, GC*, and underlying models is given in Figure 1 and the same representation showing the specific model and configuration version numbers in the GC4 NWP Case Study Suite (u-br658) is shown in Figure 2 as an example. Future versions of the ACCESS-S system may be based on GC4, or potentially later GC versions.

Figure 1: A diagrammatic representation of the relationship between ACCESS-S, GC, the GC components and the models these components are running. The Bureau's seasonal coupled model is based on the GC model from the UKMO. The GC model consists of global atmosphere, land, ocean and sea ice components, coupled together using a coupler called OASIS. Each of these components is based on a separate model (UM, JULES, NEMO and CICE respectively) configured to run on global grids. Each of these models and components has separate version numbers, denoted by the italic letters a to k in this diagram.

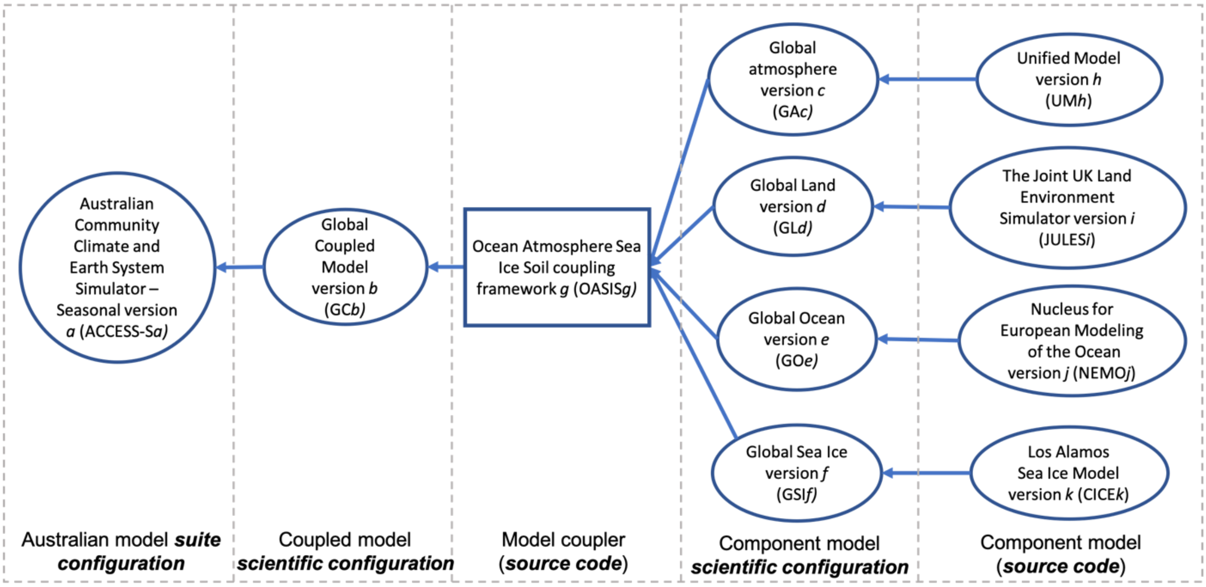
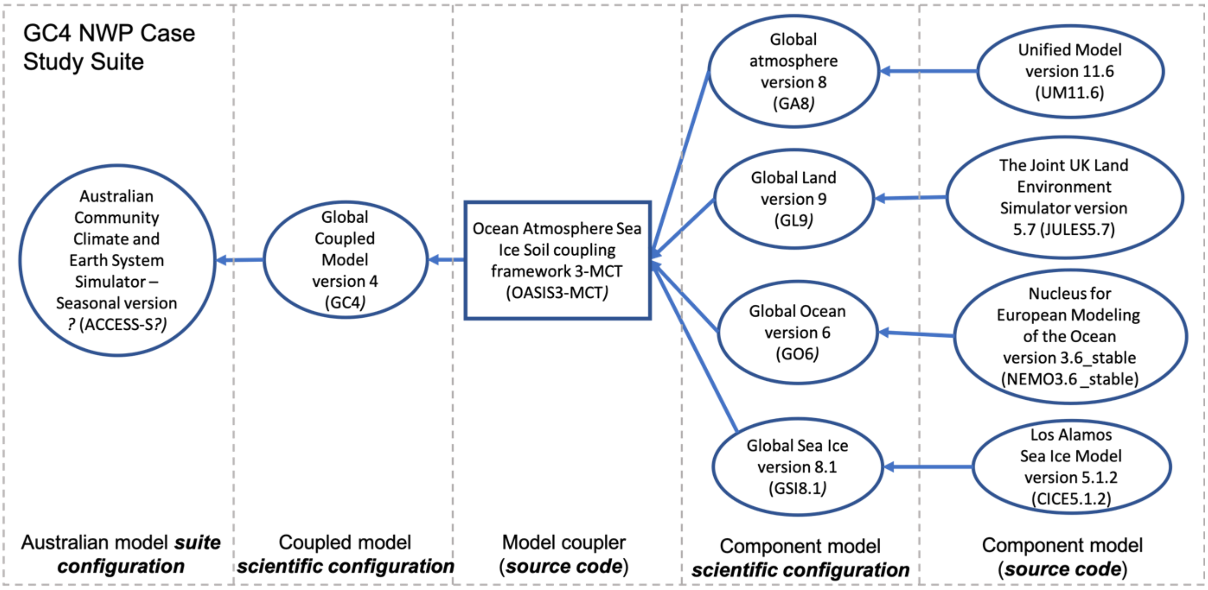


Figure 2: The same model relationship representation as Figure 1, but specific to the GC4 NWP Case Study Suite (u-br658). Future versions of the ACCESS-S system may be based on GC4, or potentially later GC versions.



1.3.2 Coupled Suite porting and development

Two versions of the UKMO Global Coupled model 4 (GC4) have been ported to the National Computational Infrastructure (NCI) supercomputer Gadi, which is main supercomputer used by BoM to test new modelling systems. These versions are:

- A Coupled Climate Assessment suite (ID u-bs992)
- A Numerical Weather Prediction (NWP) Case Study suite (UKMO ID u-br658, ported IDs u-cl383 and u-cl384)

These suites have significantly different configurations, and extensive work was required to overcome configuration, platform, dependency, and compiler issues.

Porting the atmosphere and land components of GC4 was reasonably straightforward, while porting the ocean and sea ice components posed more of a challenge. This was in large part due to the greater degree of technical and infrastructure support available on NCI systems for the atmospheric components, through the Australian Community Climate and Earth System Simulator (ACCESS) collaboration and the ARC Centre of Excellence for Climate Extremes (CLEX). This has highlighted the need for an uplift in this kind of support for the ocean and sea ice components in the future. We expect that going forward more infrastructure and technical support will be available at NCI, which should expedite this process.

This work was done in consultation with colleagues within the Bureau and NCI and collaborators at the UKMO. A major benefit of the work is the strengthening of collaborative ties both within the Bureau and NCI, and to the UKMO. This will be of benefit to future model porting a development work which is undertaken.

Our main focus going forwards is the NWP Case Study suite (u-cl383), which will be used to perform rapid assessment of model biases and scientific validity over the case study period (24 start dates across 2013 and 2014). This suite enables us to bring over and locally test model upgrades such as CoMorph (under ID u-cl384) and the latest versions of the coupled model (e.g. G4, GC5), and evaluate how well these models and improvements perform for predicting northern Australia climate. It also provides a test to investigate scientific questions such as the computational cost and scientific impact of enabling new local improvements such as interactive vegetation in a coupled model.

As a baseline, we have completed a set of 24 5-day runs and 24 5-week runs of this suite and are in the process of evaluating them. We have also upgraded the suite to a newer version of the software UM12.1 (under ID u-cl383) and completed baseline runs of this upgraded version. Finally, we have created a GC4.CoMorph version of the suite with UM12.1 (under ID u-cl384) and have completed baseline runs of this version as well. We are now in the process of evaluating these GC4.CoMorph runs against observations and against u-cl383. This will be the first assessment of the performance of CoMorph in a coupled model forecast suite.

Future work for this suite includes:

- Updating the suite design to better match that of the Coupled Climate Assessment suite, since that design is more portable and generalized. This work is being undertaken with the support of collaborators at the UKMO, with the intention of merging it into the main GC* reference suite. This will mean that going forward, all future suite improvements at the UKMO and at BoM can be shared and co-developed.
- Moving from running off ECMWF start dates to using UKMO ones, which will allow a bigger set of case studies to be conducted
- Extension from a deterministic suite to an ensemble suite that allows the evaluation of probabilistic products
- Updating the suite to run over a more recent case study period (e.g., 2018/19)
- Investigating methods to run the suite in a more computationally efficient seamless configuration (by degrading spatial and time resolution with lead time for example)
- Design and creation of a multiweek hindcast suite to facilitate more comprehensive evaluation of model improvements.
- Updating the suite to produce a more useful and customized set of output fields relevant to Australia.

1.4 Results

1.4.1 Porting of models from the UKMO to the BoM

Both u-bs992 and u-br658 were successfully ported to the Gadi supercomputer, and the latter was upgraded to UM12.1 (under suite ID u-cl383) and had CoMorph added (under suite ID u-cl384). Although the version of the coupled model in u-bs992 and u-br658 was the same (I.e., GC4), the suite configurations were quite different, and the model was set to run differently between the two (for example, running on different timescales, running from different types of input files etc.).

The designs for climate and NWP suites each follow a common framework respectively which are markedly different from each other, so porting both these suites had the benefit of exposing the author to both suite designs and allowing them to identify the benefits and drawbacks of each. This is valuable knowledge since it informs future work designing more portable suites in collaboration with the UKMO.

Since these suites were quite different, porting each was a significant amount of work. That is, while the work done to port the first suite (the coupled climate assessment suite) did inform the work of porting the NWP case study suite, there were also new challenges which arose from porting this second suite.

The design of u-bs992 was more amenable to porting to new machines, which is probably a consequence of the greater degree of international collaboration on GC* coupled climate simulations compared to GC* coupled NWP simulations. Adopting a suite design like that of u-bs992 across timescales would facilitate greater collaboration between the Bureau and the Met Office through more rapid adoption of model upgrades at the Bureau on all timescales. A common suite design between the Bureau and the UKMO, and across timescales would also make it easier for Bureau staff to develop model improvements and contribute them back to the Met Office to be included in future model releases.

In comparison, while being less portable, u-br658 is simpler in design and is configured to run at shorter timescales of days to weeks. This makes it a more practical suite for use for some of the work planned for the coming year (e.g., testing CoMorph in a coupled run, and rapid validation of new model configurations and releases). This suite is therefore intended to be the focus of development work, with u-bs992 serving as a template for future work to improve the portability of u-br658 (and u-cl383/u-cl384).

A major change in the design of the NEMO model which was implemented between the version used in GC2 (which underpins the Bureau's current operational coupled seasonal model ACCESS-S2) and the version in GC4 is the adoption of an IO server XIOS to handle file reading and writing. This significantly improves the runtime of the NEMO component of the coupled model. A version of XIOS suitable for use with NEMO as it is configured in GC4 was not available on Gadi, and so had to be built manually. This process was technically challenging, however the benefits to model runtime were immediately apparent.

Another key outcome from this porting process has been the identification of infrastructure gaps at NCI (e.g. the lack of a suitable pre-built version of XIOS). The infrastructure supporting the atmospheric and land-surface components of the coupled model are well supported at NCI (for example, a wide variety of standard static files are readily available for use, and all dependencies are pre-built and maintained by system administrators) through the Australian Community Climate and Earth System Simulator (ACCESS) collaboration and the ARC Centre of Excellence for Climate Extremes (CLEX). In contrast, the lack of support for the ocean, sea-ice and coupler components of the model was striking. One outcome of the porting work has been to highlight these differences and motivate for the need for greater support for all components of the coupled model. Work is underway to address these issues, which is expected to result in faster model porting and an improved coupled model research and development environment on NCI infrastructure in the future.

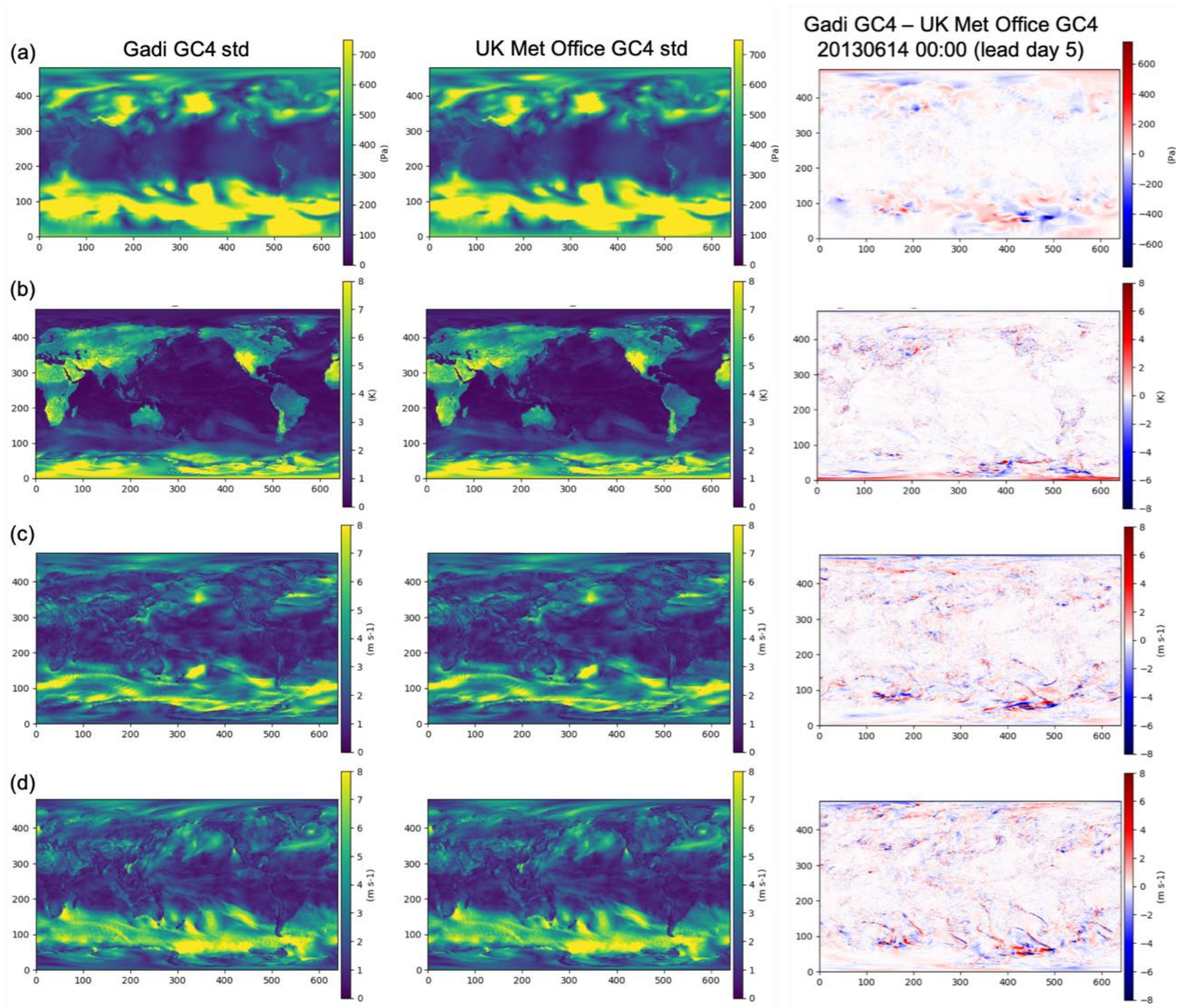
1.4.2 Testing the scientific validity of GC4 on Gadi

To test that the outputs of GC4 on Gadi are scientifically valid, 5-day baseline runs were performed in the ported version of u-br658 that were identical to those done at the UKMO. These were then directly compared. While they are not expected to be identical (due to the effect of different compilers and rounding errors), they should agree to within the noise in the model. That is, the degree of difference between them should be less than or comparable to the variability within each run.

To check this, the standard deviation of the UKMO and Gadi runs were computed along lead time and compared to the difference between the UKMO and Gadi runs on day 5. This was done for mean sea level pressure, surface temperature, and u- and v- wind components (zonal and meridional flow). The results of this for a single run (start date 20130614) are shown in Figure 3. It can be seen from this figure that in each of the variables examined the magnitude of the largest differences between the two runs at lead day 5 is comparable to the largest values of the standard deviation in each of the runs. This is a good indication that the version of GC4 ported to Gadi is functioning as expected and is producing scientifically valid results.

In total, 24 5-day runs and 24 5-week runs of version u-br658 ported to Gadi have been completed. A more comprehensive analysis of these, and comparison observations is desirable, and is planned to be undertaken in the coming months.

Figure 3: Comparison of 5-day runs of GC4 from the UKMO and on Gadi for start date 20130614. The left column shows the standard deviation along lead time of the Gadi run, the middle column shows the standard deviation along lead time of the run obtained from the UKMO, and the right column shows the difference between the two runs on day 5. Row (a) shows sea level pressure, (b) shows surface temperature, (c) shows zonal (u) surface wind and (d) shows meridional (v) surface wind.



1.4.3 Indo-Pacific PEG

A comprehensive evaluation of model bias was carried out as part of the Indo-Pacific PEG and the results were presented in a workshop in 2020. This work was done in collaboration with UKMO partners and ECMWF (they have similar model problem). The evaluation pointed to the primary cause of the biases likely coming from the atmospheric model and more specifically convection over the Maritime Continent. However, the evaluation also pointed to other areas that were potentially also contributing to the bias, including the ocean model and the initialisation, which were making the evaluation much more complicated. A set of activities to be coordinated by the PEG were agreed and are underway. These are listed below together with organisations leading each activity:

1. Rossby Wave propagation through IT (BoM)
2. Throughflow properties and impact on mean bias in NEMO ORCA (UKMO/NACP)
3. Air-sea interaction properties/biases across timescales (UKMO)
4. Indian Ocean Teleconnections with Monsoon and monsoon forecasts (NCMRWF, India)
5. Ocean/Atmos bridge between Pacific/Indian (NIWA, New Zealand)
6. Evaluation of SST/Precipitation/Wind relationships over Indian Ocean (ECMWF)
7. Ocean reanalyses in the Indian Ocean (BoM)
8. SF skill of IOD (ECMWF)
9. How Good is GC4/5 in the Indian Ocean + common diagnostic package (BoM/NACP)
10. Impact of CoMorph on Indian Ocean (BoM/UKMO/NACP)

NACP has made significant contribution to PEG activities (2), (9) and (10).

1.5 Conclusion

1.5.1 Key findings

Both a climate (u-bs992) and an NWP (u-br658) configuration of GC4 have been ported to the NCI infrastructure and run successfully. Initial tests of the scientific validity of GC4 on Gadi indicate it is running correctly and producing results which are comparable to those obtained from the UKMO. Versions of the NWP configuration have been upgraded to UM12.1 (u-cl383) and further upgraded to include CoMorph (u-cl384).

The process of porting GC4 to the NCI infrastructure has highlighted weak points in the support for coupled models there, which can now be addressed. Additionally, motivated by the outcomes of this porting work, a shared, portable reference suite is now being developed jointly by the BoM and the UKMO. This will facilitate more rapid adoption of new model versions from the UKMO and enable increased contribution of Australia-focused improvements back into future model versions.

This availability of the latest frozen GC release from the UKMO on Gadi has enabled the development and testing of model improvements such as CoMorph over Australia, and contribution to activities such as the Indo-Pacific PEG. This will in turn expedite the work of proving improvements are stable for inclusion in the next GC model releases from the UKMO and will help to inform future development activities through the outcomes of activities such as PEGs In turn, this will lead to more accurate and reliable model configurations available from UKMO for future versions of ACCESS-S. This will ensure that model development which prioritizes skill gains over Australia is included in model releases, ultimately leading to better forecasts for agriculture and the Australian public.

1.5.2 Benefits to industry

A critical need of the industries in northern Australia is more accurate multi-week and seasonal forecasts. The BoM uses coupled models from UKMO in its seasonal prediction system ACCESS-S. In the past BoM took models developed at UKMO with little input of Australian needs. The benefits of this component are the establishment of a modelling infrastructure framework which ensures that

Australian scientists have input into the new models being developed at the UKMO and are able to measure how well those models meet the needs of northern Australian industries at the time that they are being developed. This means that future model versions will be better for northern Australia and in turn lead to better multi-week and seasonal forecasts from the BoM.

1.6 Future research and recommendations

This work represents the beginning of a new approach to coupled model development and research at the Bureau. GC4 is the latest frozen global coupled model release from the UKMO. Going forward, the intention is to port each new version to BoM as it becomes available, so that (1) any bugs identified can be rapidly addressed and the fixes passed to the UKMO, and (2) model improvements important for Australia can be more rapidly developed, tested and incorporated into future GC releases. Essentially, the aim is to spend less time playing "catch up" with model versions and more time improving the model jointly with UKMO.

Each new GC version ported will increase the expertise of staff at the Bureau and will inform improvements to the supporting infrastructure at BoM. It is expected therefore that the process of keeping pace with UKMO model releases should become easier with time.

There are several avenues for further work on the GC* model at NCI, the most obvious of which is upgrade from GC4 to GC5 when it is made available in 2022, and eventually to GC6 in 3-4 years' time.

Additionally, the following improvements to the suite would be desirable:

- Development of an updated GC* reference NWP assessment suite which is portable between the UKMO and the BoM and is co-developed between them;
- The suite currently uses *startdump* files (initial conditions the model uses to start a run) obtained from the European Centre for Medium Range Weather Forecasting (ECMWF). The availability and acceptable use of these is limited for the Bureau, and so it is recommended that u-cl383 and u-cl384 be adapted to run off startdumps produced at the UKMO, and potentially in the long-term from startdumps produced at the Bureau;
- The u-br658 suite is a deterministic suite (only one ensemble member). To better represent uncertainty in forecasts and to improve the statistical significance of analysis done on model runs, it is recommended that u-cl383 and u-cl384 be extended to an ensemble system (i.e., multiple forecasts of the same period, each run with slightly perturbed initial conditions);
- Extend the suites to be able to run for a more recent set of dates which includes some significant events in the Australian region (e.g., the 2019 Queensland floods, Cowan et. al. 2019);
- Design and creation of a multiweek hindcast suite to facilitate more comprehensive evaluation of model improvements;
- Updating the suite to produce a more useful and customized set of output fields relevant to Australia.

It is also recommended that contributions to the development and testing of model improvements such as CoMorph are continued. Furthermore, it is recommended that the research suites at the BoM are used to contribute to the Indo-Pacific PEG and other PEGs which are likely to result in research outcomes that will ultimately lead to improved forecast skill over Australia.

1.7 References

Cowan, T., Wheeler, M. C., Alves, O., Narsey, S., de Burgh-Day, C., Griffiths, M., ... & Hawcroft, M. K. (2019). Forecasting the extreme rainfall, low temperatures, and strong winds associated with the northern Queensland floods of February 2019. Weather and Climate Extremes, 26, 100232.

2. Model convection improvements at the Met Office

Sally Lavender [1,2], Matt Hawcroft [1,2], Sean Milton [1]

1 University of Southern Queensland, Toowoomba, Queensland, Australia

2 UK Met Office, Exeter, United Kingdom

2.1 Background

The Bureau of Meteorology (BoM) uses versions of the Met Office Unified Model (UM) for forecasting purposes at all timescales. Seconding USQ/NACP staff to the Met Office accelerates model development that specifically focusses on model skill over northern Australia.

The majority of precipitation in the tropics is convective. Convective clouds act to transport heat, moisture and mass upwards, fuelled by the latent heat release of condensing water from rising air parcels. Since this motion can't be represented on the resolved model grid, the convective parameterisation represents the effects of this dynamical process by estimating how much the transport affects the temperature and moisture of the atmosphere around it. As such, whether the convection scheme in a model adequately represents the spatial and temporal distribution of convective precipitation and diabatic heating has implications not only for local precipitation accumulations but also for the wider circulation through convective-dynamical coupling.

For a generation, the Met Office convection scheme has been based on the mass-flux approach of Arakawa and Schubert (1974), in which the role of the convection scheme is to stabilise atmospheric profiles via the removal of CAPE (convectively available potential energy) through subsidence within a grid column. The existing scheme lacks much of the structural flexibility required to address systematic biases generated by convection in the UM. In addition, with the growth in capability of regional modelling at kilometre scales, a scheme that can be scale-adaptive is required. To address this, a new convection scheme called CoMorph is in the final stages of development at the Met Office and a USQ/NACP staff member has been fully integrated in this development process. CoMorph has been tested extensively as part of NACP particularly for the performance over northern Australia and ability to represent important processes such as the MJO.

2.2 Objectives

Contribute to the development of the new UM convection scheme with a particular focus on phenomena with known influence on northern Australian weather and climate processes. As part of the analysis of performance over the NACP region is the development of a suite of analysis tools that can be used by others at the Met Office.

2.3 Methodology

Extensive testing of CoMorph, and the current convection scheme, have been undertaken in a wide range of UM configurations including the idealised and single column models as well as an aquaplanet alongside more commonly used climate and NWP (numerical weather prediction) configurations. Use of multiple different configurations of the UM as well as a standalone version of CoMorph enables a wide variety of conditions to be tested. In addition to comparing results from CoMorph against other model global atmosphere (GA) science configurations (see 'global model evaluation at the Met Office' final report) and observations, these have been used to test parameters within the convection scheme to ensure they are set appropriately and that changing them has the theoretically expected effect.

The CoMorph simulations use a full package of changes, not only to the convection scheme but also other physics that interacts with this scheme.

2.3.1 Global climate runs

The atmosphere-only model is run for 20-years and the CoMorph (version A) output is assessed relative to the latest, GA8, configuration and observations where available. These have been run at various resolutions but the N96 results are shown here.

2.3.2 Idealised studies and parameter testing

CoMorph has been tested extensively in idealised setups as part of NACP2. These have been used extensively since the initial branch of CoMorph was made available mid-2019. Without having researchers based at the Met Office, particularly within the convection group, this would not have been possible.

2.3.2.1 Sensitivity to humidity

For models to sufficiently represent convective clouds, they must capture the relationship between convection and mid-tropospheric humidity. This moisture-convection relationship is also known to be important for simulating the MJO (e.g. Kim et al. 2014). The experimental setup has been kept as similar as Derbyshire et al. (2004; see paper for full experimental details) as possible although accounting for a higher model top in more recent versions of the model. The model is initialised and relaxed back to profiles of potential temperature, zonal wind and relative humidity (RH). There are 4 different experiments with values of RH of 25%, 50% 70% and 90%. Idealised and single-column (SCM) versions of the model using this set up have been used alongside a standalone version of CoMorph which doesn't have the interaction of the other model physics. Various configurations including a high-resolution convection resolving setup (CRM), as well as multiple GA configurations with and without CoMorph have been carried out over a range of horizontal resolutions and domain sizes.

2.3.2.2 The MJO and equatorial waves

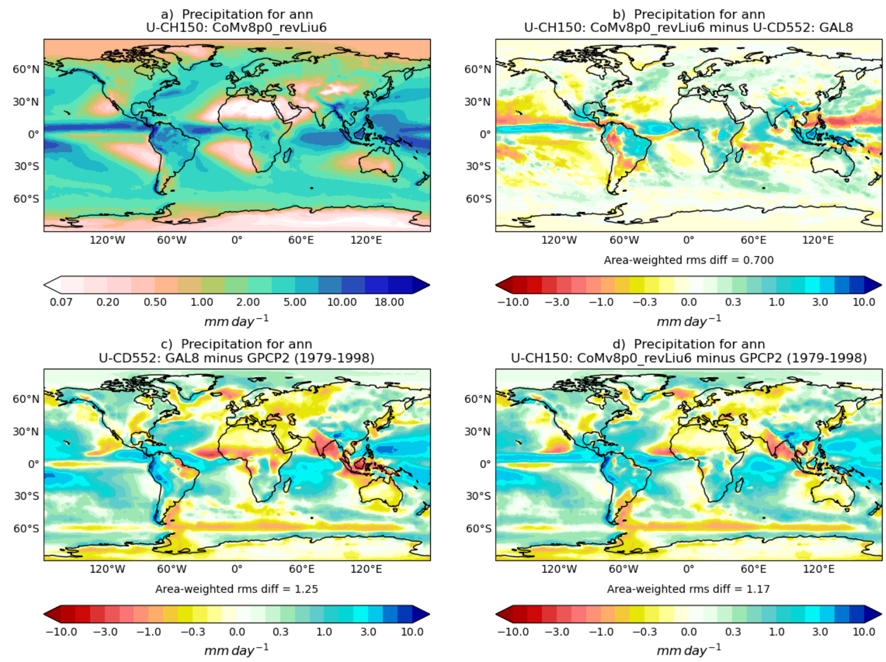
Aquaplanet experiments have played a key role in MJO related research in the scientific community since the influence of the continents, particularly the maritime continent where many models struggle to allow propagation of the MJO, is neglected. Initial aquaplanet experiments are based on Leroux et al. (2016) with zonally symmetric SSTs and an imposed 'warm pool' region of higher SSTs. An additional experimental setup for investigating the MJO is the NWP hindcast suite to simulate an observed MJO event based on the same technique used by Klingaman and Woolnough (2014). Using this set up (see original paper for methodology) the influence of entrainment rate on the December 2018 MJO event is investigated, initialising the model from UM analyses on 4th December.

2.4 Results

2.4.1 Global climate model performance

Fig 1 shows the global annual mean precipitation for the CoMorph run and differences from GA8 and observed values. Additional plots of variables mentioned in the text can be found in the NACP2 Milestone 9 report. There are evident improvements in CoMorph, particularly in the increase in precipitation over tropical land, including the maritime continent. There is a slight increase in precipitation over India but still the large dry bias over this region remains. Overall, the RMSE (root mean squared error) is reduced. This improvement is also seen in the total column water vapour where the tropospheric dry bias over tropical land considerably reduced resulting in a large reduction in RMSE. Timestep intermittency still seen in GA8 is removed in CoMorph, although averaging in space or time gives similar statistics between the two (not shown).

Figure 1: Annual precipitation from (a) CoMorph, (b) CoMorph minus GA8, (c) GA8 minus observations (GPCP) and (d) CoMorph minus observations.



The diurnal cycle is generally worse in CoMorph than GAL8 although this varies by region. Ongoing work to couple CoMorph to a cold-pool scheme should help to substantially improve this. Additional analysis of forecast runs (not shown) show there is enhanced spurious convection at local noon that is widespread in CoMorph but away from local noon there are indications of CoMorph capturing rainfall events missed by GAL8.

CoMorph is found to produce a considerable increase in high cloud over tropical land which is a notable improvement. There is also more low cloud, improving the low-latitude negative bias, but broadening the mid-latitude excess. This change in the cloud also affects the shortwave and longwave cloud-forcing (not shown). There is a significant decrease in the RMSE of the shortwave cloud forcing, mostly due to stronger forcing (more cooling) over land and in strato-cumulus regions as well as the southward shift in the band over the Southern Ocean. The RMSE of the longwave cloud forcing is also improved significantly, mainly due to increased cloud forcing (warming) over tropical land. Additionally, the RMS error in surface fluxes (not shown), which are important for coupled models, is reduced which seems to be due to notable improvements in the tropical West Pacific and stratocumulus regions. However, there is some degradation in the North Atlantic.

There are positive signs regarding both the MJO and convectively coupled equatorial Kelvin waves (CCKW) which have stronger signals than in GA8. This is an area of focus for the idealised testing work that has been a significant part of the NACP contribution to CoMorph development.

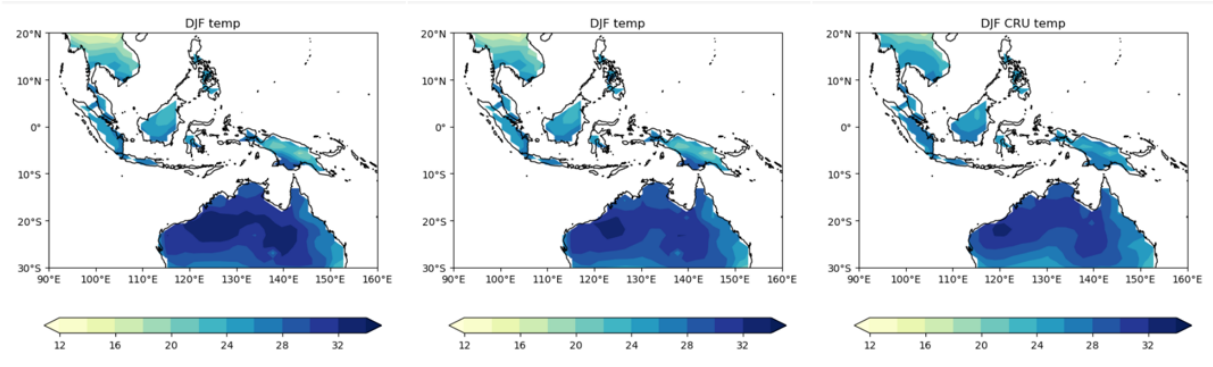
Another important feature to capture and with relevance to the NACP region are tropical cyclones (TCs). There are two main regions where models in general do poorly when simulating TCs, with too many systems in the central Pacific and too few in the North Atlantic. CoMorph shows improvements with regards to this with fewer TCs in the central Pacific and more in the North Atlantic than GA8 (not shown). The wind-speed pressure relationship is also improved for all basins and intensities.

Results from seasonal NWP trials at N320 show a good improvement of 1.9% and 0.6% in JAS and DJF respectively of CoMorph over GA8.

2.4.2 Australian and maritime continent performance

As part of NACP, a new assessment area covering northern Australia and the maritime continent has been developed. This is part of a tool that is routinely used by model developers at the Met Office and allows a focus on the performance of the model over this region without further analysis.

Figure 2: Plot of DJF averaged 1.5 m temperature from (left) GA8, (centre) CoMorph and (right) observed (CRU). Taken from the northern Australian and maritime continent assessment area.



Over Australia, the dry bias (Fig 1) has been reduced and there are improvements in the annual cycle (not shown). The Maritime continent precipitation has also improved significantly in all seasons. The warm bias evident over the Australian continent in GA8 has been reduced (Fig 2). There is little difference in the mean low-level winds (not shown), although the annual cycle of the Australian monsoon index is found to be improved in CoMorph during the pre-monsoon season but degraded in the dry summer months.

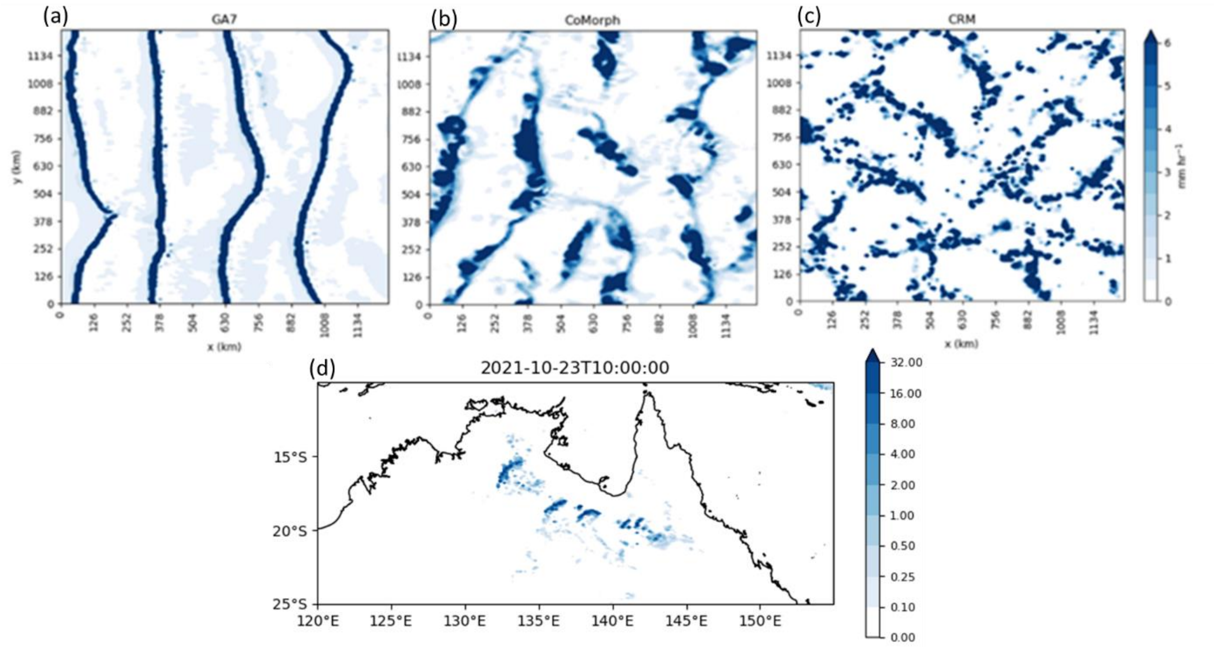
2.4.3 Idealised studies and parameter testing

2.4.3.1 EUROCS – Sensitivity to humidity

Initial experiments with this setup showed spurious convective lines that propagate against the background flow in GA7 runs (Fig 3a). In contrast, CoMorph and the CRM (Figs 3b,c) both propagate with the background flow. Further investigation of these lines found that these were frequently observed in the global NWP model, including over northern Australia (Fig 3d). This is a useful test-case for testing fixes to this issue and is a valuable experimental setup for evaluating the model during development of CoMorph. In the latest science configuration, GA8, imposing a physically reasonable minimum closure time scale along with the inclusion of a prognostic entrainment rate and time-smoothed convective increments has led to the removal of these lines.

This experimental set-up has also been useful for estimating parameters from the CRM and comparing with those used in CoMorph. For example, the entrainment rate in the CRM can be calculated in two ways, theoretically as the gradient in moist static energy or by estimating a parcel radius at each height using image processing techniques. These can then be compared with the value in CoMorph. This idealised setup has pointed out issues with the sensitivity to moisture and height of the cloud-top.

Figure 3: Snapshot of precipitation rate 4 days into a simulation with 70% RH from (a) GA7, (b) an early version of CoMorph (both 10 km resolution) and (c) 1 km resolution CRM, regridded to 10 km, over 1260 km^2 domain. (d) GA7 NWP run at N1280 (~10 km) initialised on 21st October 2021.



2.4.3.2 The MJO and equatorial waves

As development of CoMorph has progressed there have been positive signs regarding its ability to simulate a reasonable MJO. At various stages in CoMorph development this has been improved considerably and has been consistently better than GA8. Some of the improvements in the MJO were at the expense of the Kelvin-wave response which were slowed down considerably. This has now been fixed and the amplitude of the Kelvin waves is improved from recent GA configurations.

A combination of aquaplanet experiments, climate simulations and NWP hindcasts have allowed detailed analysis of effect of the entrainment rate on the MJO. Previous analysis of the MJO in GCMs suggests the MJO signal can be improved, at the expense of mean-state biases, by increasing the entrainment rate (e.g. Klingaman & Woolnough 2014) which increases the sensitivity to the surrounding environment. In CoMorph, a high (low) entrainment rate results in a smaller (larger) MJO signal but stronger (weaker) KW signal. Reasons why the increase entrainment rate is having the opposite effect in CoMorph than previous model versions are likely due to the improved coupling to the dynamics and other model physics.

2.5 Conclusion

2.5.1 Key findings

This report gives an overview of the performance of CoMorph in climate and NWP configurations as well as an insight to the testing that has formed in integral part of NACP research at the Met Office.

The performance of CoMorph is very positive and, although there is still ongoing work to improve the diurnal cycle, is an improvement on the previous scheme.

A version of CoMorph was put forward for consideration into the next global atmosphere version, GA9. Although the results were all seen to be very promising it was decided, due to a very fine timeline for the 'freezing' of GA9, that it was too new and recent to be included at this stage. However, CoMorph development has resulted in improvements to other model physics that will be included in GA9, highlighting the indirect benefits of developing the new convection scheme. For full details of all these changes see the report produced for NACP2 Milestone 9.

Although there is potential to develop CoMorph further over the coming years, a CoMorph package has been released to UKMO partners, including the BoM. This allows users at the BoM to get used to the new scheme and provide additional testing/feedback before the updated version is released next year. CoMorph is the future of convection modelling at the Met Office and will be included in future GA releases. It is unfortunate that the final stages of development have occurred at the same time as the transition of the Met Office to the next generation modelling system, LFRic, where there is a pause in model releases.

2.5.2 Benefits to industry

Integrating USQ/NACP researchers directly into the Met Office has enabled BoM to have access to CoMorph and the results of simulations during the development process much earlier than waiting for an official science configuration release from the Met Office. If there is shown to be significant improvement for northern Australia, then CoMorph may be included in the next seasonal model at the BoM prior to inclusion in a Met Office GA release. This would not have been possible without NACP.

The Australian-focussed assessment tool, which has been developed as part of this project, will be used in future model development at the Met Office. This also paves the way for including these metrics in future versions ESMValTool (Eyring et al. 2020) which has wide usage across the climate modelling community (e.g.CMIP).

The ability of NACP to leverage the research tools (e.g. computing resources) and world-leading expertise (Met Office personnel) has been hugely beneficial to the project.

2.6 Future research and recommendations

We recommend the following for future research and development:

- Continuation of the CoMorph development work (as further improvements are made to the scheme) with further testing and application to the Australian, Maritime Continent and Indian Ocean regions, using a range of modelling techniques.
- Application of the latest CoMorph version to multi-week prediction of extreme events using the coupled ensemble suite (see 'global model evaluation at the Met Office' final report).
- Deeper analysis of CoMorph's local improvement (Indian Ocean and Maritime continent) links to remote teleconnections (improved diagnostics) and sub-seasonal to seasonal variability (e.g., the MJO), with deeper analysis of the impacts over northern Australia.

In addition, there are several related projects that USQ/Met Office project scientists will be able to engage with and leverage from that are of interest to proposed future work related to convection in the UM (see NACP2 Milestone 9 report for further details).

2.7 References

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3. Global model evaluation at the Met Office

Matt Hawcroft [1,2], Sally Lavender [1,2], Alison Stirling [1]

1 University of Southern Queensland, Toowoomba, Queensland, Australia

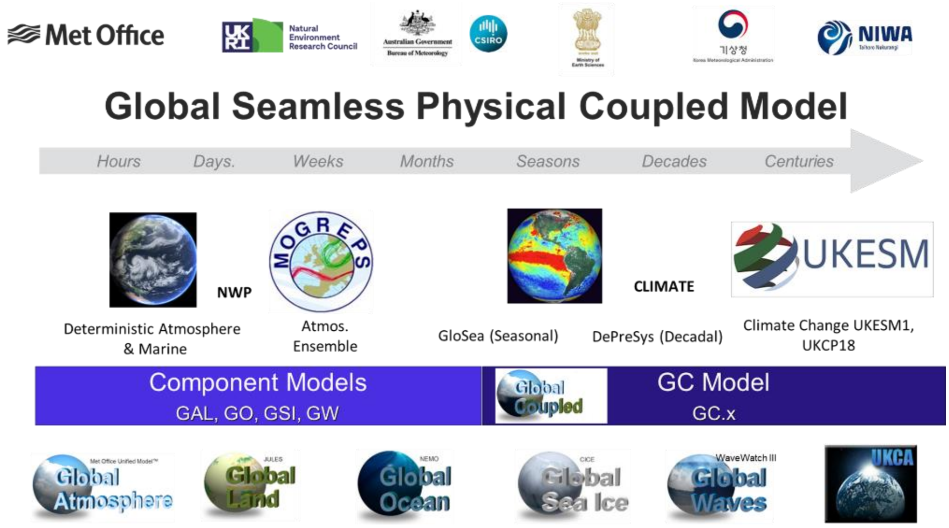
2 UK Met Office, Exeter, United Kingdom

3.1 Background

The Bureau of Meteorology (BoM) uses versions of the Met Office Unified Model (UM) for forecasting purposes at all timescales. Seconding USQ/NACP staff to the Met Office accelerates model development that specifically focusses on model skill over northern Australia.

As part of the Met Office's wider model development pathway, the model is in a state of continuous development, with new global coupled (GC) science configurations 'frozen' and released periodically, which bring together new strands of research/development into a single model configuration (e.g. Fig 1) for rigorous testing, assessment and analysis. For example, Global Coupled configuration 3.0 (GC3.0; Williams et al. 2017) comprises component configurations Global Atmosphere 7.0 (GA7.0), Global Land 7.0 (GL7.0), Global Ocean 6.0 (GO6.0), and Global Sea Ice 8.0 (GSI8.0). These new versions are then used for research and operational purposes at all timescales from NWP (numerical weather prediction) and seasonal through to decadal and climate simulations. From Spring 2022 GC will be used at NWP timescales (previously atmosphere-only) resulting in a seamless application of GC across all timescales. During the project, GC4 has been frozen and assessed (unpublished), and GC5 is in a late stage of testing with 'freezing' anticipated in early 2022. A key area of the NACP-funded work is understanding the ability of these new versions of the model to represent weather and climate phenomena relevant to northern Australia, such as the Madden-Julian oscillation (MJO) and Indian Ocean dipole (IOD), and to identify the physical causes of specific biases material to the region. The BoM's current seasonal forecast system is based on GC2, so understanding how seasonal prediction skill might be improved using GC3, GC4 or GC5 informs their future seasonal prediction strategy.

Figure 1: Diagram of GC model and components.



3.2 Objectives

Evaluation of the latest (and developmental) model configuration simulations of weather and climate phenomena relevant to northern Australia and to identify the physical causes of specific biases material to the region.

3.3 Methodology

3.3.1 Global coupled models

The UM is run at numerous different timescales using different experimental setups. Here we provide an overview of those simulations that have been important for analysis during NACP2.

Detailed analysis of GC2, GC3.1* and GC4 20-year climate runs have been analysed in detail at N216 (60 km horizonal) resolution. These include the GA6, GA7.1 and GA8 atmosphere components respectively. For the GA9 results, only output from a 20-year N96 resolution simulation (~135km horizontal spacing) are discussed.

The BoM uses ACCESS-S for seasonal prediction, which is based on the GC2 model. Until 2021, the Met Office's seasonal prediction system, Glosea, was also based on GC2 (Glosea5). It was upgraded to GC3.2 in early 2021 (Glosea6). As such, much analysis within NACP was undertaken using Glosea5/GC2 prior to the introduction of Glosea6, to understand biases which would impact skill in ACCESS-S. A first season of forecasts and hindcasts using Glosea 6/GC3.2 has recently become available.

One benefit of the Met Office partnership to NACP has been the ability to run and evaluate simulations using the Met Office computing infrastructure, including working with Met Office personnel to co-develop tools and simulations. A 'nudging' suite has been developed at the Met Office (Rodriguez and Milton 2019) where the winds and temperature fields across the whole of the global model atmosphere (global nudging), or a specified part of it (regional nudging), can be relaxed back towards the analysis state. This allows an ability to probe regional sources of errors versus those that are remotely forced, which then provides the capacity to perform focussed analysis on the local processes

*GC3.1 and GC3.2 are the climate and NWP versions respectively.

which drive these errors. These experiments incur considerable computing expense and would not have been feasible without Met Office resources.

3.3.2 The Indian Ocean Dipole (IOD)

The IOD is a sea surface temperature (SST) index measuring the temperature gradient from the western (IODW; 50—70E, 10S—10N) to eastern Indian Ocean (IODE; 90—110E, 10S—0S). When the index is 'positive' the west-east gradient is enhanced, indicating convection and rainfall will be suppressed in the east. The opposite is true in a 'negative' phase, when SSTs in the east are warmer, the SST gradient relaxes and rainfall typically moves westward, with dry anomalies over the Maritime Continent islands. For northern Australia, negative phases of the IOD typically bring wetter weather, with drier years associated with IOD positive years. This makes predicting the IOD at seasonal timescales particularly important for the region.

3.3.3 Ensemble suite for case studies

Using computing facilities at the Met Office at no cost to the project, a series of related ensemble suites were developed to evaluate the predictability of the February 2019 Queensland flooding event (Hawcroft et al. 2021). Ensemble prediction is particularly useful for extreme events, which may be difficult to predict in a deterministic (single simulation) framework. By running multiple forecasts, which typically have small perturbations to their initial conditions, physics or both, a spread of forecast outcomes is achieved. This allows a probabilistic assessment of forecast likelihoods. Where the possibility of high-impact events is shown in those forecasts, warnings may be issued by the forecast agency or other partners.

The investigation started from a baseline of a GA6 N216, atmosphere only ensemble of 25 members. GA6 is the atmospheric component of the GC2 coupled model. The basis for this is that operational NWP at the BoM and Met Office uses an atmosphere only model (the Met Office is moving to coupled NWP in Spring 2022) and the seasonal prediction systems at the time of the work used the GC2 model at N216 resolution (the Met Office now uses GC3.2). The ensemble was then altered to (1) increase resolution to N768, (2) improve the model physics to GC4/GA8 and (3) incorporate a coupled, dynamical ocean with a GC2/GA6, N768 atmosphere.

Additionally, two other ensembles were developed; a 'nudged' ensemble, where the model atmosphere is relaxed towards reanalysis across the whole globe or in a specified region and a 'nested' ensemble where a regional high-resolution model was nested in the lower resolution global model (4.4.km vs 60km). See Hawcroft et al. (2021) for full details of all model ensembles used in this suite.

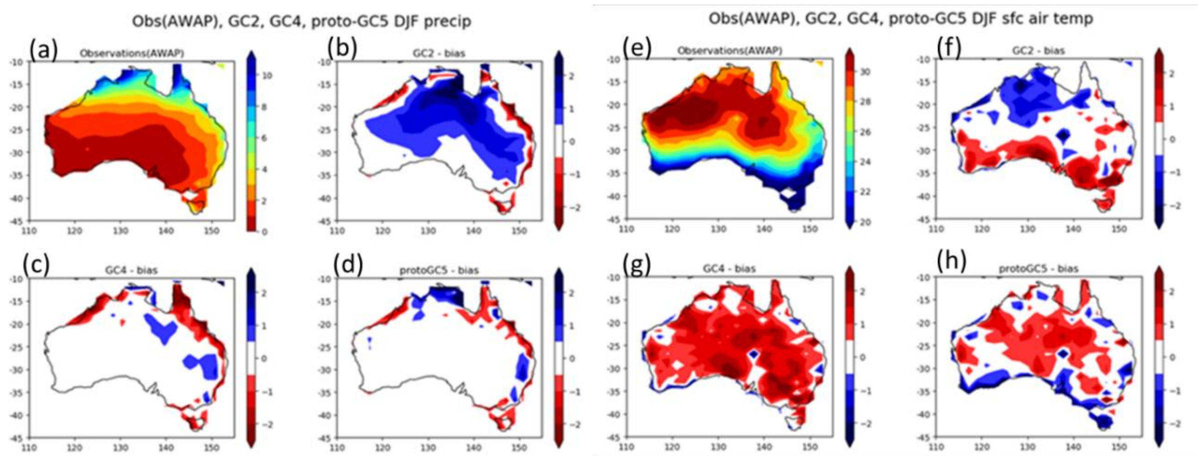
3.4 Results

3.4.1 Global coupled model performance

In moving from GC2 to GC4 (via GC3.1) there are several improvements in model behaviour relevant to the NACP region. The mean state precipitation and temperature summer (DJF) biases over Australia are reduced considerably (Fig 2). The structure and variability of tropical Pacific precipitation has improved, including the frequency of El Niño occurrence in the model climate, providing promise for seasonal prediction of a key control on monsoon precipitation. The structure and propagation of the Madden-Julian Oscillation (MJO), a key feature of tropical intraseasonal variability, improves, suggesting greater ability to predict active/break phases of the monsoon may be achievable. There is a large reduction in temperature biases in the Southern Ocean, which can impact tropical performance in the model through altering the large-scale circulation. The frequency and spatial distribution of the smaller scale convective events which dominate tropical precipitation generally improve, including over northern Australia.

Fig 2 also shows results from a developmental version of GC5 (proto-GC5). The change in precipitation bias from GC4 to proto-GC5 is mixed with a reduction in the dry bias over Cape York but a larger wet bias over the top end. The warm bias over almost all of Australia that was introduced in GC4 has been reduced in proto-GC5.

Figure 2: (a) Observed (AWAP) precipitation (mm/day) and biases for N96 (b) GC2, (c) GC4 and (d) proto-GC5 simulations during December-January. (e-h) same for near surface air temperature (C).



3.4.2 Diagnosing Indo-Pacific errors

Certain key errors have persisted in the model, which helped shape the focus of Met Office work within NACP. These include errors in both the mean state and variability of Indian Ocean SSTs and precipitation, which have impacts in northern Australia via modifying the atmospheric circulation.

3.4.2.1 Climate model errors

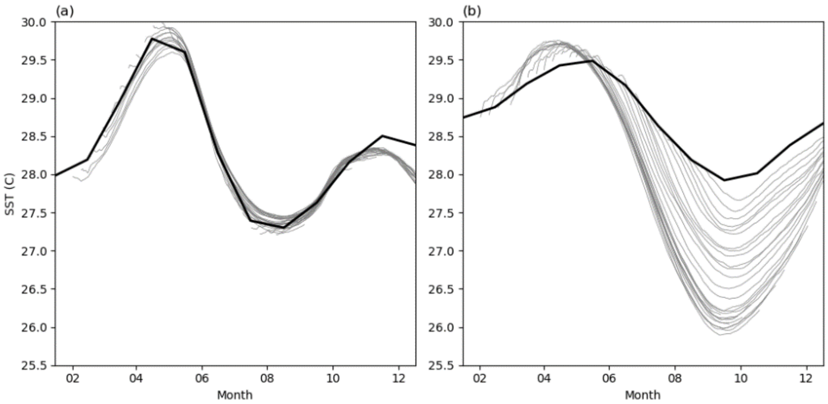
The model SSTs are generally too cool across the Indian Ocean, particularly the eastern part, during the whole annual cycle. The substantial cold error in the IODE region from July – November in GC2 is reduced in both GC3 and GC4, with GC4 exhibiting some retrogression in skill from GC3.

Extensive further analysis using different versions of the model with a variety of atmosphere and ocean resolutions and evaluating both atmosphere-only and coupled simulations identify the source of the SST errors is in the atmosphere, but that the ocean has the capacity to amplify these errors. It is of note that the atmosphere only simulations have more similar errors in their wind fields than in the coupled simulations, indicating that coupled atmosphere-ocean feedbacks play a key role in amplifying these errors. The southern and south-easterly wind stress bias off the Sumatran coast from June-August can be related to the emergence of cold SST biases in the coupled simulations, as these wind stresses would be expected to promote Ekman upwelling off the Java/Sumatra coast in a coupled framework. The magnitude of that error growth then modulates the overall coupled response, either through a wind-evaporation-SST feedback, as the localised increase in temperature gradients increases the wind speed, or through a remote forcing due to coupled errors evolving elsewhere in the model climate.

3.4.2.2 Seasonal forecast errors

Fig 3 shows the ability of Glosea5 hindcasts to predict seasonal evolution of the SSTs which form the IOD Index. For the IODW region (Fig 3a), the model consistently exhibits reasonable skill in predicting the seasonal cycle of the SSTs with a cold bias forming towards the end of the year. For the IODE region (Fig 3b), the model has a persistent cold bias which peaks in October. The evolution of the bias does not appear to be strongly dependent on the start date as the trajectory of the error is similar for hindcasts started from February through to August. This implies that the error is not strongly controlled by remotely forced errors, such as those associated with the South Asian monsoon circulation. If this were the case, it might be expected that the error trajectory would exhibit some sensitivity to the start date as the monsoon transition occurs into boreal summer.

Figure 3: Plot of 1993—2016 climatological hindcast SSTs from Glosea5 (grey) against monthly climatology from analyses (black) for (a) IODW and (b) IODE. Each grey line represents the 216-day hindcast climatology from a given start date (4 dates per month between February and August).



There is a substantial and promising reduction in the SST errors in Glosea6 (GC3.2) (not shown). Interestingly, the near surface wind biases do not reduce in a manner consistent with the improvements in the SST patterns. Biases to the south of the IODE region (centred on 90E, 15S) are eliminated in September and October and it may be that this localised reduction in wind stress is particularly material for the upwelling errors seen in GC2.

3.4.2.3 Nudging simulations

Both coupled climate and seasonal hindcast simulations show the evolution of a consistent circulation and SST error in the East Indian Ocean and it is apparent that other regions around the Indian Ocean and Maritime Continent exhibit consistent biases. By nudging selected regions to understand the remote impact of these biases, it is found that the largest biases are locally sourced to the central Indian Ocean. These act independently of the biases which emerge off the Sumatra/Java coast in coupled simulations and seasonal forecasts. Errors in the Southern Ocean do not appear to impact the east Indian Ocean substantially, but do alter the flow over Australia, which would directly influence seasonal predictability in northern Australia. One potential source of these biases is the convection scheme used in the UM.

3.4.3 Case-studies

The original 2019 floods paper (Hawcroft et al. 2021) focussed on a one-week lead time (with the event occurring in week two) and showed that an ensemble approach has the capacity to provide useful information to decision makers with over a week's notice. This is beyond the duration of many operational deterministic forecasts. Increasing model resolution and improvements in the physics had little benefit to forecast skill for this event. Ocean-atmosphere coupling played a clear role in improving forecasts of the trajectory of the low-pressure system. The behaviour of the convection scheme also introduced biases in the distribution of precipitation across northern Queensland, particularly in the atmosphere only simulations. The nudged ensemble suggested the forecast error was principally sourced in the region around the low, rather than sourced from a remote location (e.g. the Southern Ocean or Maritime Continent). The nested ensemble highlighted biases associated with the behaviour of the existing convection scheme and that by replacing the parameterised convection scheme with kilometre-scale convection permitting simulations, some notable precipitation biases were removed.

Two further events occurred during NACP which provided opportunities to run and evaluate the ensemble framework. They were an unusual heavy rainfall and flooding event in May 2020, which occurred to the south-east of Broome and impacted one of USQ/NACP's *Climate Mates*, who was unable to move livestock from her property. The second event was Cyclone Seroja, which caused significant damage and loss in Indonesia, before making landfall near Kalbarri in Western Australia in April 2021. Operationally, neither event was skilfully predicted at longer lead times. Both these events showed a similar result with clear benefits of using an ensemble framework with a one-week lead time.

3.5 Conclusion

3.5.1 Key findings

The substantial improvements to the model performance with the upgrades from GC2 to GC3 and GC4 are evident. Benefits to seasonal predictability via the recent upgrade of the Glosea seasonal system to GC3.2 have also been shown. Preliminary analysis of a low-resolution proto-GC5 simulation suggests that some improvements seen in GC3/4 have been maintained and enhanced, though the SST biases in the east Indian Ocean may have been degraded. Further, detailed, analysis of the model will be undertaken once it is frozen and N216 assessment simulations are available.

A coupled ensemble forecast/hindcast suite has been developed to assess the ability of the model to predict extreme events on multiweek timescales and will allow future events to be analysed in detail. It has demonstrated the benefits of both the ensemble framework and coupling to forecast skill and the ability to provide probabilistic information on the likelihood of such events. This demonstration of skill helps to inform the BoM's operational development strategy.

3.5.2 Benefits to industry

In addition, as part of NACP, a new automated model assessment tool covering northern Australia and the Maritime Continent has been developed. This software is routinely used by model developers at the Met Office and allows a focus on the performance of the model over this region without further analysis. This also paves the way for including these metrics in future versions of ESMValTool (Eyring et al. 2020) which has wide usage across the climate modelling community (e.g. CMIP).

Integrating USQ/NACP researchers directly into the Met Office has enabled the project to leverage the supercomputing resources (at no cost), access existing analysis and software tools which are directly relevant to this project, and exploit the intellectual resource (e.g., access to world-leading expertise provided by the ~500 research staff engaged in model development at the Met Office) that otherwise would have not been available. This knowledge and tools are then transferred back to the BoM. An estimate of cost of the computing resource for the Hawcroft et al. (2021) paper alone to an external user is on the order of AUD125,000.

3.6 Future research and recommendations

We recommend the following for future research and development:

- Detailed evaluation of GC5, at higher resolution, after it is frozen in early 2022. GC5 includes convection changes which are anticipated to alter tropical performance relative to GC4 and how these change phenomena of interest to northern Australia (e.g. mean state and variability in the Maritime Continent, the MJO, the IOD and ENSO) will be the focus of this work. Extending this to use CoMorph (see 'Model convection improvements at the Met Office' final report) will form a closely related strand of research. The potential to improve the representation of the MJO, for example, would provide a material benefit to sub-seasonal prediction skill in northern Australia, given the role of the MJO in modulating wet and dry phases of the monsoon.
- Within a coupled modelling framework, further work would be undertaken on identifying the source of model errors, both remote and local to Australia. The recent research focus has been the Indian Ocean Dipole, and expansion into ENSO (for multi-annual) and the MJO (for sub-seasonal) predictability would both be aims of future work.
- Further development and application of novel diagnostic techniques, such as the nudging framework discussed in this report, with Met Office colleagues as well as application of ensemble suites for extreme events.

In addition, there is the ability of USQ/Met Office staff to leverage off several planned Met Office projects of relevance to NACP (see NACP2 Milestone 9 report for full details of these).

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4. Multiyear Climate Predictability & Hindcast Skill

Sharmila Sur[1,2], Harry Hendon[2], Oscar Alves[2]
1 University of Southern Queensland, Toowoomba, Queensland, Australia
2 Bureau of Meteorology, Melbourne, Victoria, Australia

4.1 Background

Australia experiences multiyear droughts and pluvials that have pronounced impacts on a wide range of climate-sensitive sectors including agriculture. Improved understanding and predictive capability of multiyear climate variation is thus potentially of great value for climate resilience and decision making and is an emerging area of scientific research. El Niño-Southern Oscillation (ENSO) is the largest source of climate variability around the world, including regional Australia via atmospheric teleconnections (McBride and Nicholls 1983; Taschetto et al. 2020), and is arguably the most predictable climate mode at seasonal timescales (Tang et al. 2018).

Recent national and international research efforts have demonstrated that dynamical climate prediction systems based on coupled global climate models can skilfully forecast ENSO and its regional impacts up to a year in advance. However, operational ENSO prediction with these systems is limited to 1-2 seasons, e.g., the Bureau of Meteorology (BoM) provides climate forecasts up to 6-month lead time only, precluding the climate prediction over Australia beyond a year. Furthermore, the research on the feasibility of accurately predicting long-lasting or multiyear ENSO events had not been explored prior to NACP2. Thus, improving our understanding and predictive capacity of ENSO, including prediction of El Niño and La Niña events and their related climate impacts beyond a year will be crucial for developing a framework for multiyear climate forecasting over Australia, which has been of high importance for NACP2.

4.2 Objectives

This study aims to deliver new and fundamental research on the basic science of multiyear wet/dry conditions and multiyear ENSO as well as an assessment of the feasibility and potential predictability for multiyear climate forecasts using various dynamical prediction systems, with a focus on northern Australia.

4.3 Methodology

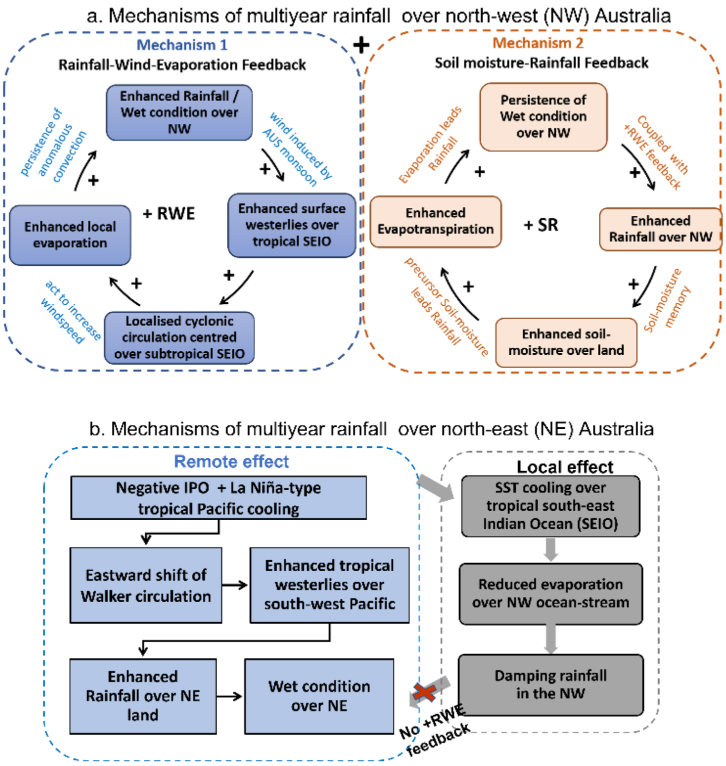
We explored observational and reanalysis datasets (1901-2017) to identify key drivers of multiyear rainfall variation across northern Australia. More details on various statistical methods used are published in *Sharmila and Hendon* (2020). To explore multiyear ENSO predictability and to develop a more general framework for multiyear climate prediction, we assessed large ensembles of multiyear coupled model hindcasts from DePreSys3 (UKMO; 1960-2014) and ACCESS-S2 (BoM; 1981-2014) and 110 years of hindcasts from SEAS5-20C (ECMWF, 1901-2010, Weisheimer et al. 2021) initialised on 1st November and 1st May from 1901 to 2010 with forecast lead time of 24 months. We used standard metrices and statistical methods to evaluate the model biases, and prediction skill. We removed the model drift by subtracting the model's climatology from each ensemble forecast at each lead time before assessing the prediction skill. More details on the model, hindcasts and verification methods are available in the previous milestone reports and submitted manuscripts (e.g., Sharmila et al. 2022a; Weisheimer et al. 2022).

4.4 Results

4.4.1 Improving the basic science of multiyear wet/dry conditions over northern Australia

This research identified regional asymmetry in multi-year rainfall variation across northern Australia and proposed underlying mechanisms on the physical drivers of that emphasised dominant role of ENSO in driving multi-year droughts in north-eastern (NE) Australia, while local feedback between rainfall, wind, evaporation in combination with sub-surface soil moisture memory modulate multi-year rainfall in north-west (NW) Australia, published in *Scientific Report* (**Figure 1**; Sharmila and Hendon 2020).

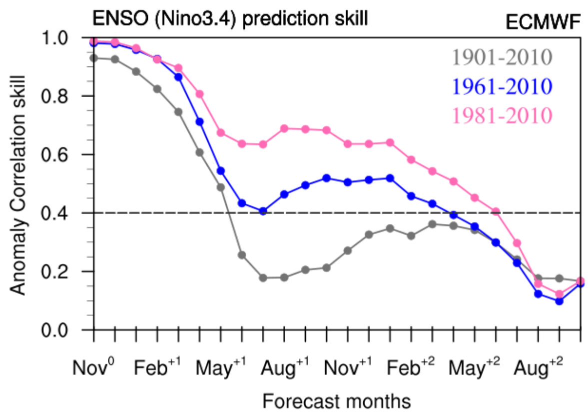
Figure 1: Schematic of the driving mechanisms for multi-year rainfall variability over (a) NW, and (b) NE Australia (Source: Fig. 8 of Sharmila and Hendon 2020, Scientific Report).



4.4.2 Advancing knowledge on predictability and hindcast skill of multiyear climate variability

This research delivered documentation of insights on fundamental questions related to ENSO predictability and multiyear climate prediction by assessing experimental large ensembles of multiyear hindcasts from UKMO, BoM, and ECMWF. Initial assessment with limited ensemble hindcast sets from ACCESS-S2 (BoM) and DePreSys3 (UKMO) systems show modest predictive capability at lead times beyond 2 years. Therefore, in the second half of the project we focused on 2-year predictions and extensively utilised the 110-years of 2-year long hindcasts from ECMWF (SEAS5-20C) to address predictability aspects.

Figure 2: Anomaly correlation coefficient (ACC) skill of ensemble mean monthly Nino 3.4 anomaly as a function of forecast lead months initialised on 1 November for selected hindcast periods: 1901-2010, 1961-2010, and 1981-2010 using SEAS5-20C hindcasts



The capability to predict ENSO is quantified using the monthly Nino 3.4 index (area mean SST: 5°S-5°N, 170°-120°W). Analyses from ECMWF show that ENSO can be skilfully predicted up to about 1.5 years in advance from Nov-initialised forecasts (**Figure 2**; Sharmila et al. 2022a). However, the skill also has multidecadal variation (*Appendix: Figure M1*), displaying a strong sensitivity to the hindcast period (Weisheimer et al 2022). We also found that La Niña in year 2 is more predictable than El Niño.

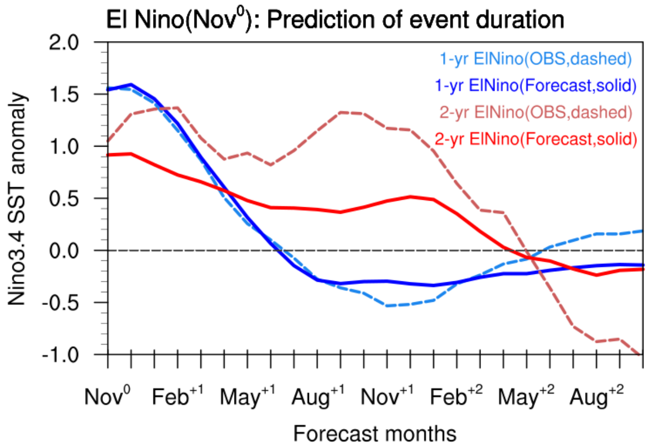
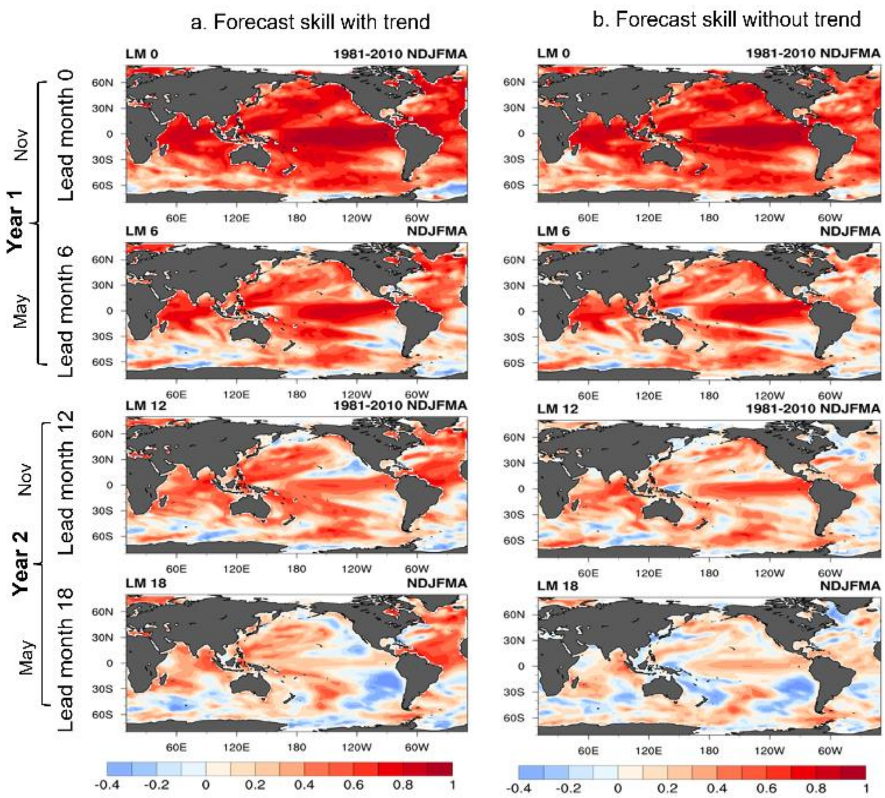


Figure 3: Composited time evolution of Nino3.4 index (°C) of 2-year ensemble mean forecasts (solid line) initialised near the peak El Niño in November (Nov^0) and corresponding observation (dashed line) for 1-year El Niño (blue), and back-to-back El Niño (red). (Source: BOM Annual Report 2020-21).

A significant finding of this research is that forecasts can usefully predict if a current El Niño or La Niña will terminate in the following year or continue for at least another year (**Figure 3**; Sharmila et al. 2022b). Back-to-back El Niño years typically lead to a period of prolonged drought, so the ability to predict El Niño beyond one year would be very valuable to climate-sensitive industries. As a result of these findings, the BoM will investigate extending its ENSO outlooks up to 2 years into the future, compared to the current 6 months (*BOM Annual Report 2020-21*).



The 2-year prediction of wet-season (Nov-Apr) global SST anomalies (**Figure 4**; Sharmila et al. 2022c) is skilful over most of the oceans especially in the equatorial Pacific region. The warming trends in the tropical Indian Ocean and north Atlantic also contributed to the overall skill, signifying the role of climate change on multiyear climate prediction.

Figure 4: 2-year prediction skill of northern wet-season (Nov to Apr) mean sea surface temperature (SST) for forecasts with (left) and without (right) trend for recent period (1981-2010) initialised at 1 Nov and 1May.

For regional climate, reasonably good skill is evident in predicting Australian rainfall for year 1 reflected from well-predicted ENSO-rainfall teleconnection (*Appendix: Figure M2*). However, many challenges remain as evident from the limited skill in predicting year 2 rainfall and relatively low prediction skill in regional surface temperature – so more investigation on model biases and process-oriented understanding of climate predictability would be necessary to enhance predictive skill and higher degree of confidence in future real-time operational forecasts.

4.5 Conclusion

This study provides new insights on the science of multiyear climate variability and predictability, especially focusing on long-lead ENSO predictability and its multidecadal variation of skill. We also provided new insights in the dependence of prediction skill on initial state, predictability of multiyear ENSO events and their teleconnections to Australian climate. These findings are valuable for developing an operational multiyear climate prediction framework using BoM's climate forecast system, ACCESS-S.

4.5.1 Key findings

- Identified underlying mechanisms of observed multi-year rainfall variation across northern Australia.
- ENSO can be skilfully predicted up to at least 18 months in advance, while strong decadal variation in skill is also detected.
- Asymmetry found in long-lead forecast skill between El Niño and La Niña – where La Niña in the year 2 is more predictable than El Niño.
- High predictability of 2-year or multiyear ENSO events signifies the prospects for extending seasonal operational forecasts by one additional year.
- Substantial skill in 2-year prediction of global SST, and good skill in predicting wet-season rainfall over NE Australia beyond year 1, reflected from well predicted ENSO-rainfall teleconnection.
- Skilful multiyear ENSO prediction provides a new foundation for forecasting prolonged droughts and widespread flooding at multiyear timescales.

4.5.2 Benefit to industry

The key findings through NACP2 are highly beneficial to Australian industry:

- Improved industry and community knowledge of multiyear climate variability and droughts.
- Key driver for the Bureau of Meteorology's future strategy for developing operational long-range ENSO prediction framework (up to 2 years into the future) using the Bureau of Meteorology's climate forecast system, ACCESS-S.

- Skilful long-range ENSO prediction and development of a multiyear climate prediction framework will be useful for managing droughts, climate risk and decision making across northern Australia.

4.6 Future research & recommendations

We recommend the following for future research & development:

More research to understand underlying mechanisms of multiyear ENSO events, protracted droughts, and their predictability to support eventual real-time forecasts to users.

Further research required to understand the low skill in predicting temperature over northern Australia beyond year 1.

Further assessment of new experimental hindcast from currently operational ACCESS-S2 to provide scientific guidance for trial real-time extended ENSO forecasts out to 2 years.

BOM's future operationalisation strategy to extend ENSO outlooks at least up to 2 years compared to the current 6 months, considering user needs, benefit, and computational costs.

Future work to prioritise reducing model bias and improve the process-oriented understanding of climate predictability to achieve greater confidence in future real-time operational forecasts.

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5. Evaporative stress and flash drought

Hanh Nguyen, Matthew Wheeler
Bureau of Meteorology, Melbourne, Victoria, Australia

5.1 Background

Drought is a big challenge for graziers and has significant impact on agricultural output and productivity. An aim of NACP2 was therefore to improve the drought preparedness amongst red meat producers in the north by means of improving understanding, trust and use of climate information including knowledge of droughts and specifically flash droughts in their decision making.

The term 'flash drought' was only adopted in Australia around 2018 when the media used it to describe the experience of graziers in southern Queensland who had witnessed a drought event that had rapidly developed over the course of several weeks. This particular drought developed too quickly for the usual drought-coping mechanisms to be effectively employed. This raised the need for flash drought monitoring, early warning and forecast. Given no prior research on fast-developing drought in Australia had been conducted at the beginning of NACP2, a special focus on fast-developing droughts, i.e., flash drought, was therefore given.

5.2 Objectives

Provide understanding, indices, and tools to allow the grazing industry to make better decisions regarding flash droughts.

5.3 Methodology

Flash droughts occur when a rainfall deficit persists over several weeks and soil moisture content is depleted by evapotranspiration (ET) leading to increased evaporative stress for plants. Flash droughts are also often exacerbated by increased solar radiation, dry air, and increased wind speeds, all of which increase evaporative demand (PET for potential evapotranspiration) and the evaporative stress. The Evaporative Stress Index (ESI), which is the standardized anomaly of the ratio of ET to PET can capture the combined effects of ET and PET, is a good index to monitor plant stress conditions and flash droughts. The ESI is more indicative of drought conditions that affect agriculture and natural ecosystems than, for instance, the rainfall deficiency alone, as it can better capture the factors that contribute to the total stress on vegetation. Negative ESI values indicate above normal evaporative stress and potentially drought conditions. The ESI can be used to identify both slow-developing agricultural droughts when it falls below a certain threshold (often -1 or below the 20th percentile) and rapid intensifying droughts (i.e., flash droughts) when a sharp drop to negative ESI values (typically a drop from neutral to below -1 within a few weeks) indicating a rapid increase in evaporative stress. Two flash drought indices were derived from the ESI: rapid change index (RCI) to detect the sharp drop to negative ESI values; and flash drought index (FDI) to detect flash drought onset and duration. These indices are computed using observation-forced output of ET and PET and from the BOM's land surface landscape water balance model AWRA-L version 6. AWRA-L produces daily output on a 5km grid over Australia back to 1911. Therefore, the ESI is computed on the same spatio-temporal scale. This allowed the study of the climatology and variability of flash droughts as well as realtime monitoring. Further computational details are reported in Nguyen et al (2019, 2020, 2021). We also computed ESI from the BOM's ACCESS-S1 model forecast output to obtain a prototype flash drought forecast product.

5.4 Results

We found that the ESI is a suitable index to monitor not only long-term agricultural droughts (Nguyen et al 2020) but also flash droughts (Nguyen et al 2019, 2021,2022). To illustrate this, during 2017-2019 drought existed in many parts of Australia, with varying degrees of severity and varied timing of development and intensification. The surface conditions went from anomalously wet in 2016 to an official government-declared drought from the end of 2017. The drought subsequently intensified further to become most severe in mid to late 2019. Maps of the ESI across Australia for a sequence of key dates capturing the evolution of drought conditions between June 2019 and February 2020 are shown in Figure 1. During this most severe drought period, flash drought was identified first in Eastern Australia (Fig. 1c) then in Northern Australia (Fig. 1e). While negative ESI anomalies dominate during the period consistent with the multi-year drought, its rapid intensification leading to extreme evaporative stress (strong negative ESI anomalies) in the east and north in January 2020 was associated with flash drought. Detailed description of this event is published in Nguyen et al 2021.

After objectively defining drought and flash drought using the ESI and the case-study above, we computed drought and flash drought for all of Australia on a 5km grid with near-realtime monitoring as AWRA-L outputs are operationally produced daily. There is usually two days delay to allow computing time. The flash drought monitoring is accessible with restricted access (available to NACP for prototype use) at http://poama.bom.gov.au/project/esi/esi.html. This monitoring is computed back to 1975. The occurrences of drought and flash drought occurrences since 1975 at the eleven Climate Mate locations are shown in Figure 2 and their total numbers are given in Table 1. The superimposition of the two types of droughts shows that at any one grid point, flash drought can occur either as part of a slower developing drought event or in isolation. However, there is a tendency for more flash droughts that last longer and are more severe during the major drought events (Nguyen et al 2020).

We then produced the flash drought indices forecast from the BOM's ACCESS-S1 model forecast calibrated output. While ACCESS-S1 is skilful in simulating ESI at 3 weeks leadtime, it fails to accurately simulate the ESI temporal change therefore failing to simulate accurately the RCI and FDI. Tests indicated that it is leadtime-dependent model bias in the ET and PET that leads to this failure with options identified for correcting this issue.

Figure 4: Evolution of the 2019 flash drought sequence as depicted in the ESI from the beginning of (a) the rapid intensification (*3-Jun-2019*) to (f) the rapid recovery to normal conditions (*25-Feb-2020*). Only negative ESI values, which indicate enhanced evaporative stress on plants, are shown.

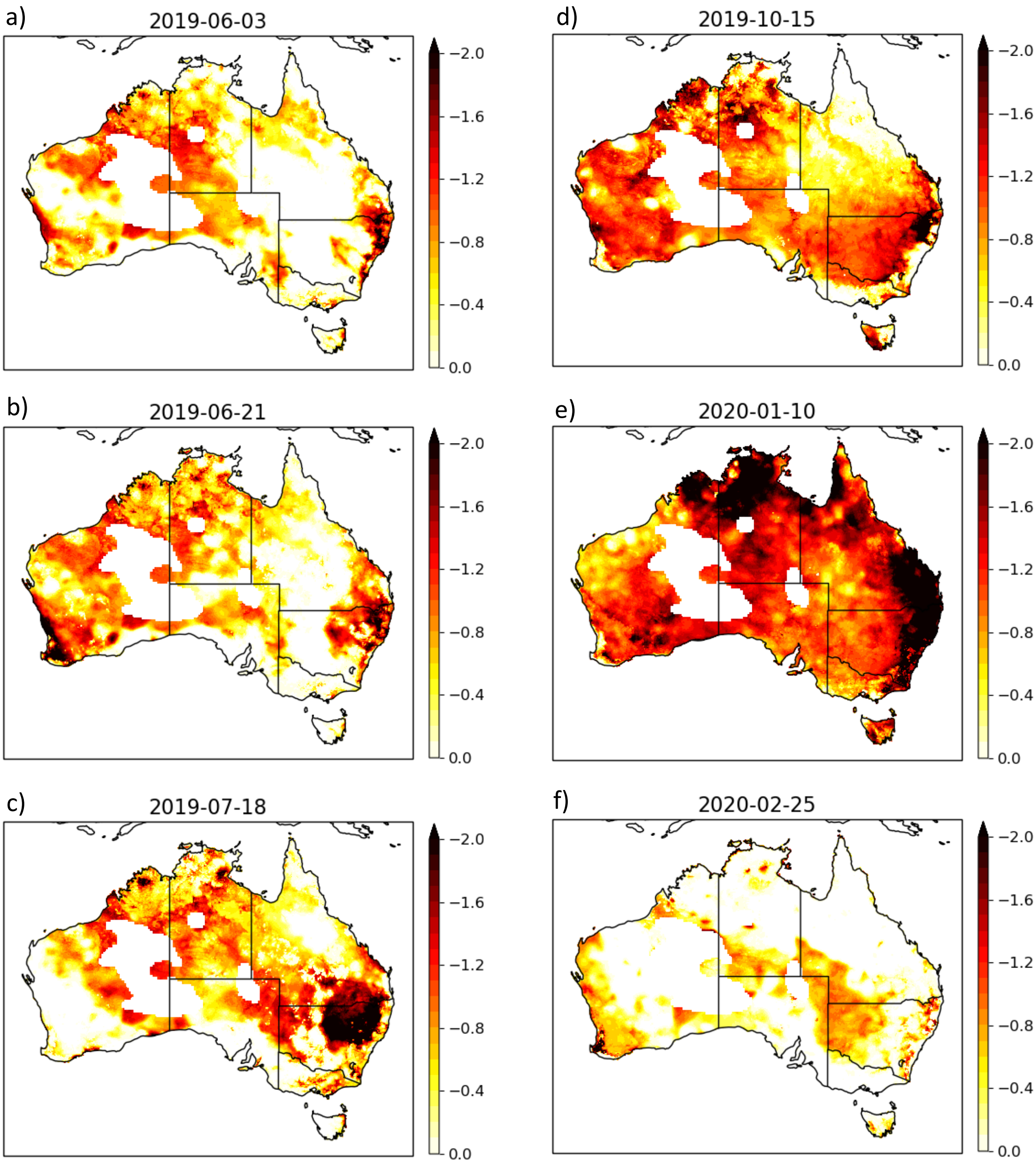

Figure 5: (top) The eleven gridpoints used, approximately corresponding to the NACP Climate Mates locations (https://www.nacp.org.au/outreach/climate_mates). (bottom) Flash drought (filled bars) occurrences for the selected eleven Climate Mates locations. The thickness of the bars indicates the flash drought duration, and the height of the bars represents the flash drought intensity. Conventional slow-developing drought events are superimposed (open bars).

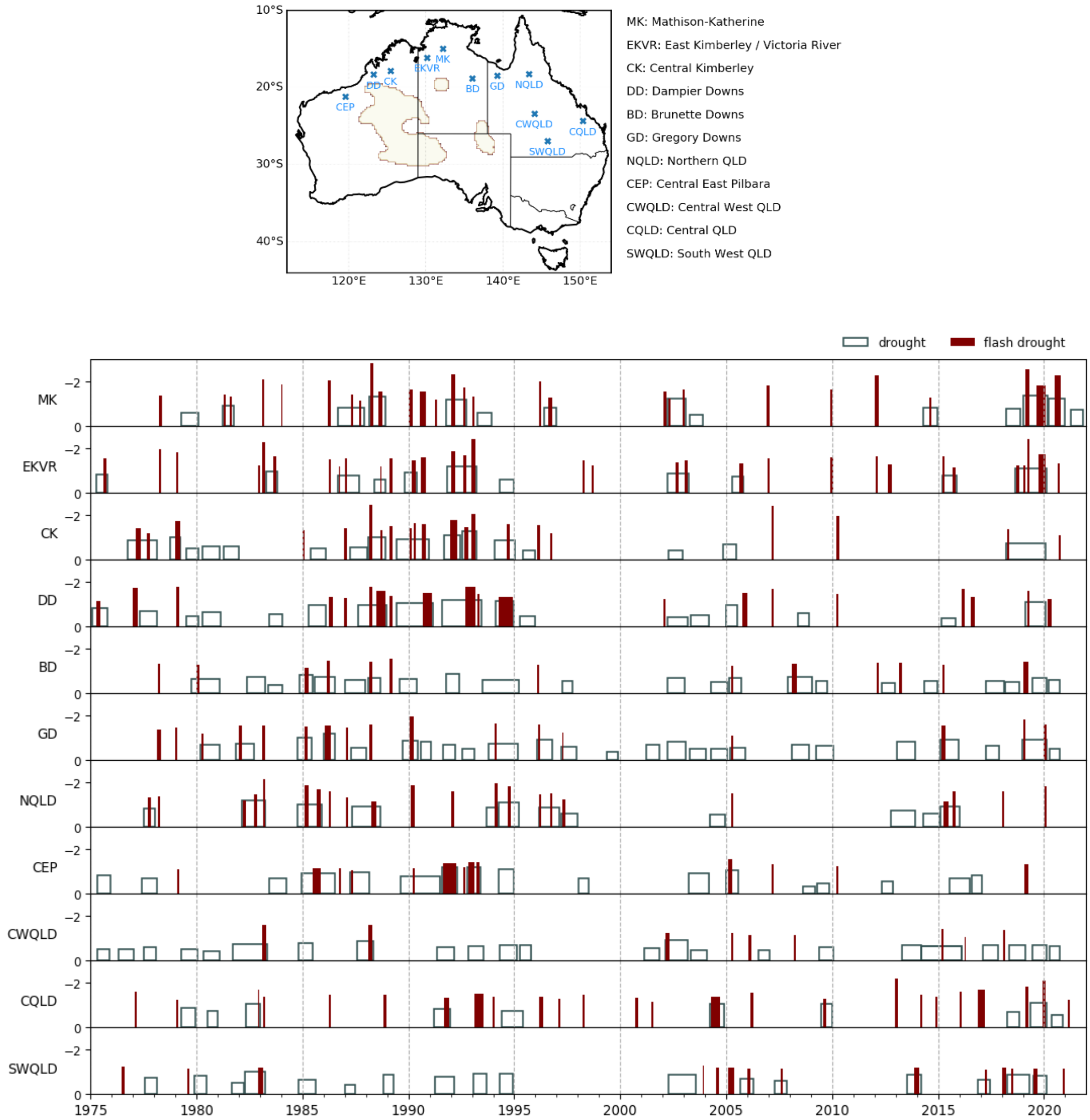

Table 1: Number of drought and flash drought events for the eleven Climate Mates locations for 1975-2021.

Cluster	MK	EKVR	CK	DD	BD	GD	NQLD	CEP	CWQLDS	CQLD	SWQLD
# D	14	11	16	17	22	25	12	17	24	10	17
# FD	28	32	21	20	13	17	22	13	9	25	14

5.5 Conclusion

5.5.1 Key findings

We found that the ESI is a suitable index to monitor not only long-term agricultural droughts (Nguyen et al 2020) but also flash droughts

We computed drought and flash drought for all of Australia on a 5km grid with near-realtime monitoring

Flash drought can occur either as part of a slower developing drought event or in isolation.

Flash drought indices forecast from the BOM's ACCESS-S1 model forecast calibrated output found while ACCESS-S1 is skilful in simulating ESI at 3 weeks leadtime, it fails to accurately simulate the ESI temporal change therefore failing to simulate accurately the RCI and FDI. Tests indicated that it is leadtime-dependent model bias in the ET and PET that leads to this failure with options identified for correcting this issue.

5.5.2 Benefits to industry

Before NACP2 there was no scientific basis for confirming the anecdotal evidence of rapidly intensifying drought as had been identified by agricultural users. With this work the industry now has that scientific basis to verify the on-ground experience. In particular, this work was the first in Australia to employ and thoroughly document the ESI as an index for monitoring the daily evolution of drought. With a resolution of 5km and historical data back to 1975, the ESI can now support the industry to better respond to an evolving flash drought on their property. This information could aid graziers to delay or move forward their decision to sell stock, purchase or distribute hay, supply additional water points for stock, or not to grow a crop.

5.6 Future research and recommendations

We recommend the following:

- Continued maintenance and testing of the ESI monitoring product into the future including upgrades as new versions of the land-surface model outputs of ET and PET become available.
- Use what was learned from the prototype ESI predictions to develop and test new methods of flash drought prediction that are skilful and without bias.

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6. Madden-Julian Oscillation (MJO) forecasting

Matthew Wheeler[1], Andrew Marshall[2]
1 Bureau of Meteorology, Melbourne, Victoria, Australia
2 Bureau of Meteorology, Hobart, Tasmania, Australia

6.1 Background

The Madden-Julian Oscillation (MJO; Madden and Julian 1972) causes variations of Australian rainfall and temperature, including extremes, on time scales of a week to a month or so, especially in Australia's north (e.g., Wheeler et al. 2009; Marshall et al. 2014). This can have potentially large impacts on many sectors including agriculture, and thus improving our ability to predict the MJO and its impacts has been of high importance for Northern Australia Climate Program phase 2 (NACP2).

Before NACP2, the Bureau of Meteorology (BoM) provided real-time monitoring of the MJO via the Real-time Multivariate MJO (RMM) index developed by Wheeler and Hendon (2004). This index gives a phase number from 1 to 8 and an amplitude to the MJO for each day based on observations of clouds and winds from around the globe near the equator. Before NACP2, the BoM also provided maps of the historical relationship between the MJO and Australian rainfall, displayed as the probability of exceeding the weekly median as a function of the MJO's eight phases. But no predictive information for the MJO was provided, and the historical maps only used data up to 2009.

Here we summarise the improvements to the understanding and prediction of the MJO that have occurred as part of NACP2, and the new products that have become available. In particular, because of NACP2 there are now MJO predictions provided on the BoM website, and new and updated historical impact plots have been prepared for publishing.

6.2 Objectives

Provide new and updated research supported MJO prediction and impact products.

6.3 Methodology

We assessed MJO prediction using the RMM index described above. MJO forecasts were generated using the ACCESS-S forecast system versions 1 (S1) and 2 (S2). S2 is the BoM's current operational coupled model subseasonal to seasonal prediction system, having replaced S1 on 20 October 2021. Compared to S1 (1990-2012), S2 (1981-2018) provides a longer hindcast dataset for our MJO prediction skill assessment. The S2 hindcasts analysed here comprise 9 ensemble members (11 members for S1), initialised twice per month for the 1990-2012 period common to both models.

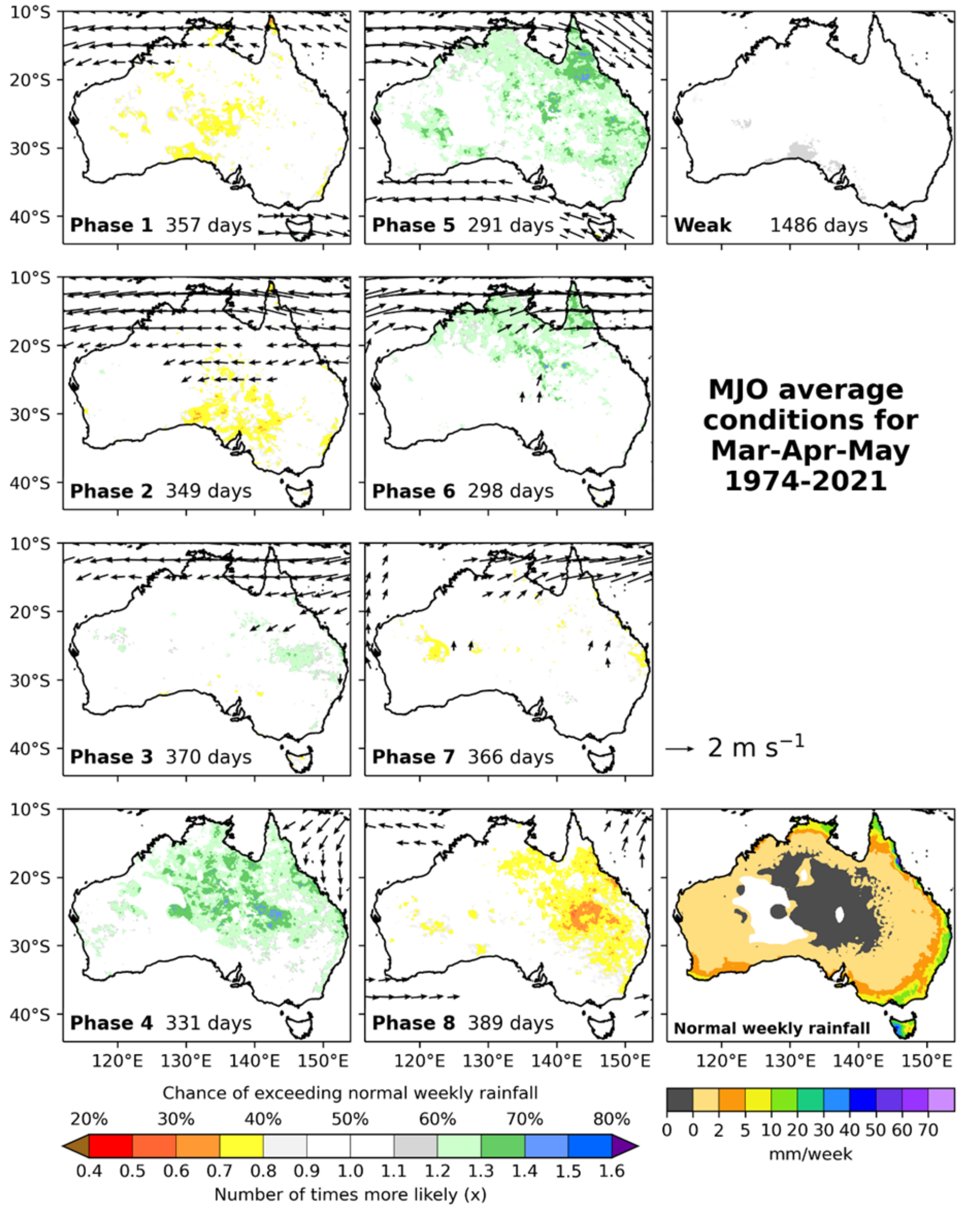
For the historical impact plots, we use the same eight RMM phases as described above and observed rainfall and temperature data up to 2021.

6.4 Results

We assessed MJO prediction skill using the bivariate correlation (COR) of Lin et al. (2008) and find that both S2 and S1 predict the MJO out to 27 days lead time for COR=0.5 which is considered the limit of useful forecast skill. Results for S1 were published in Marshall et al. (2021). This places ACCESS-S as one of the leading forecast systems internationally for predicting the MJO and shows a 4–5-day improvement in skill compared to the Bureau's previous operational coupled model prediction system (2011-2018), POAMA-2 (Marshall and Hendon 2019). This improved skill provided the scientific incentive to now display MJO forecasts on the BoM external web pages at http://www.bom.gov.au/climate/enso/#tabs=Tropics.

For the historical MJO impact plots, updated precipitation plots through to 2021 have been prepared (e.g. Figure 1; Cowan et al. 2022) and are awaiting formal journal review and publishing before they are released on the BoM website.

Figure 1: (Left and centre columns) Composites of weekly rainfall probabilities (colours) and 850 hPa wind anomalies (vectors) for Phases 1 to 8 of the MJO for March to May (MAM) over the 1974/5-2020/21 period. (Top right panel) Composite conditions for the weak MJO phase. For these composite maps, only statistically significant values at the 5% level are shown. Rainfall probabilities refer to the chance of weekly rainfall exceeding the median, expressed as a ratio with the mean probability (~50%, but less than 50% in climatologically dry regions). (Bottom right panel) The normal weekly rainfall in MAM, with the areas in white representing regions with insufficient rainfall observations.



6.5 Conclusion

6.5.1 Key findings

Both ACCESS S2 and S1 predict the MJO out to 27 days lead time for COR=0.5 which is considered the limit of useful forecast skill

6.5.2 Benefits to industry

The results summarised here provide agricultural businesses and communities across northern Australia with one of the most skilful MJO forecasts available through ACCESS-S2, improved understanding of the relationships between the MJO and Australian rainfall, and improved development of MJO forecast products using a very long hindcast dataset.

6.6 Future research and recommendations

We recommend the following for future research and development:

- Extend the historical MJO impact maps to include temperature, weather extremes, and the combined influence of ENSO, updated through to at least 2021.
- Further analyse ACCESS-S2 output on the depiction and prediction of extreme rainfall and temperatures related to the MJO with a view towards future model improvement.
- Assess the importance for Australian rainfall and temperature of other multi-week climate modes, such as the Southern Annular Mode (e.g., Marshall et al. 2012).

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7. Variability in pasture growth with ENSO, land type and region in northern Australia

Robyn Cowley [1], Kath Ryan [2]
1 Department of Industry, Trade and Tourism, Northern Territory
2 Department of Primary Industries & Resource Development, Western Australia

7.1 Background

Managing stock numbers across the wide natural variability in forage availability in extensive rangelands is a key component of good grazing land management in northern Australia. Pasture growth is driven by rainfall and soil nutrients and moderated by competition with the woody overstorey. In arid regions, pasture growth is usually water limited, so seasonal rainfall is a good predictor of seasonal pasture growth except in the wettest years when it can be nutrient limited. In higher rainfall semi-arid and mesic regions, the proportion of years where growth is water limited declines as growth becomes more nutrient limited (Mott *et al.* 1985). In nutrient limited situations, above a certain rainfall threshold, more rain does not lead to more pasture growth, the threshold varying according to site fertility. Modelling pasture growth using long term historical climate data provides insights into the variability of pasture growth for different regions and land types (McKeon *et al.* 1990, Day *et al.* 1997, Cobiac 2006). Simulated pasture growth can be analysed in the same way as rainfall, to get a better understanding of the impacts of seasonal climate drivers such as ENSO on the variability in pasture growth and seasonal carrying capacity. Simulated pasture growth is a better indicator of seasonal carrying capacity than total wet season rainfall alone, because it accounts for rainfall lost to runoff, drainage and evaporation, and the impacts of nutrients, radiation, temperature, woody overstorey, and the onset and duration of the wet season on pasture growth.

7.2 Objective

The objective was to examine how simulated pasture growth varies with ENSO across northern Australia and how this varies with region and land type productivity.

7.3 Methodology

Monthly and annual pasture growth between 1st April and 31st of March was modelled using GRASP (McKeon *et al.* 1990) version 2.1.02 and default parameter file cedardefault_v_2_1_02.prv. Land type parameter sets were chosen to represent low, moderate and high productivity land types that were relevant to modelled regions (Table 1). Modelled regions were chosen to include a wide range in rainfall (ranging from 355 to 980 mm) and ENSO influence on rainfall. Sites were located from north eastern Qld (Thalanga) where ENSO influence on rainfall is higher, to the Kimberley in WA (Halls Creek) where ENSO influence is limited (Sharmila and Hendon 2020). Long term interpolated climate files between 1889 and 2020 were downloaded from SILO https://www.longpaddock.qld.gov.au/silo/. Simulations were run with a two year spin-up to output annual and monthly pasture growth between 1891-1892 and 2019-2020.

7.4 Results

Modelled percentile pasture growth using long term historical climate records provides a guide to the variability in growth and hence safe stocking rates due to climate variability for a given location and land type (Figure 1). At all locations there was a wide historical range in rainfall and pasture growth for all ENSO phases. Median rainfall and growth were higher in La Nina than El Nino years (Figures 2 and 3). However, the La Nina phase was not a guarantee of high rainfall and pasture growth even where ENSO has more influence on rainfall. For example in the eastern Barkly (eastern NT), median rainfall in La Nina years was 50% higher than in neutral years, but rainfall in La Nina years still varied from 200 mm to 1200 mm, and pasture growth from 500 to 3500kg/ha (Figure 1).

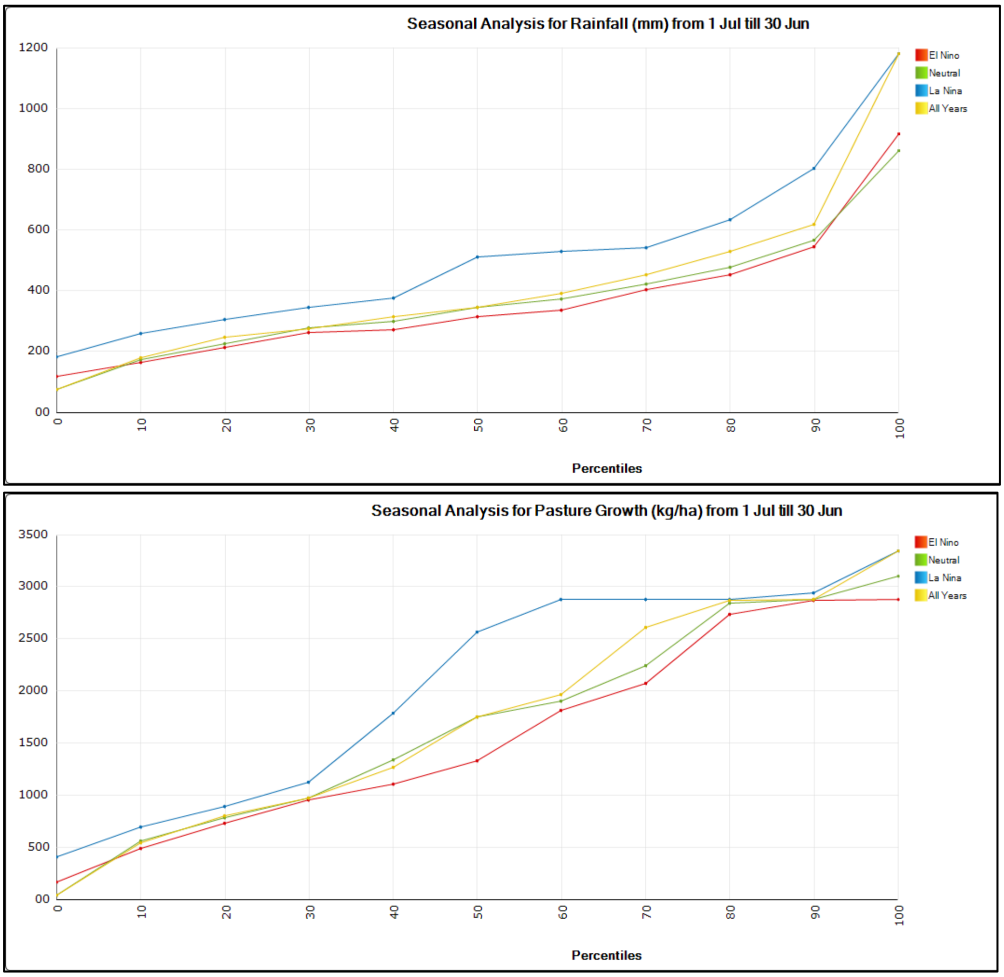

Figure 6: Percentile rainfall (top) and pasture growth (bottom) for Mitchell grass pasture in the eastern Barkly Tableland.

ENSO had a diminishing influence on inter-annual rainfall variability and modelled pasture growth from east to west across northern Australia. El Nino years had greater rainfall deficits and La Nina years had greater positive rainfall deviations in eastern than western locations (Figure 2).

The difference between median rainfall in La Nina vs. El Nino years was greatest in the east at around 60 to 65% of median rainfall at Thalanga and on the eastern Barkly, and declined to 25 to 28% of median rainfall between Katherine and Halls Creek (Figure 2). Variation in simulated pasture growth with ENSO (and hence safe stocking rate, Figure 3) followed similar patterns to rainfall, with large variation in growth and safe stocking rates with ENSO in eastern Australia, declining across to the west.

The exception to this was when nutrients limit pasture growth at higher rainfall locations and in lower productivity land types. Hence there was less variation in growth with ENSO, because rainfall was not the limiting factor to growth. This was evidenced in the reduced effect of ENSO on pasture growth at Katherine for all land types (Figure 3) and in low productivity land types at higher rainfall locations (Katherine and the Victoria River District). Rainfall is usually high in Katherine (median 980 mm, with more than 800 mm in 70% of years), and rarely limiting to pasture growth, so variation in rainfall had less effect on pasture growth. Even in drier locations with a stronger ENSO influence on rainfall, in high fertility land types such as the eastern Barkly Mitchell grasslands, pasture growth can plateau at higher rainfall. For example, in the Barkly Mitchell grass, the wettest 40% of La Nina years (when rainfall was greater than 500 mm) tended to have similar pasture growth due to nutrient limitations (Figure 1).

7.5 Conclusion

7.5.1 Key findings

ENSO had a diminishing influence on inter-annual rainfall variability and modelled pasture growth from east to west across northern Australia.

El Nino years had greater rainfall deficits and La Nina years had greater positive rainfall deviations in eastern than western locations

Nutrients limit pasture growth at higher rainfall locations and in lower productivity land types

7.5.2 Benefits to industry

Simulated pasture growth outputs in graphical (such as per Figure 1) and table form were provided to Climate Mates in the NT and WA for use in climate variability extension in their regions. Understanding the potential variation in growth with ENSO, decile rainfall, and land type, can assist cattle producers to plan for the scale of likely stocking rate adjustments required between wetter and drier periods, and the impact that ENSO is likely to have for their regions and land types. The cattle industry can also use pasture growth percentile outputs in combination with forecasted seasonal rainfall to plan stock movements and sales at the end of the dry season and as the wet season progresses.

7.6 Future research and recommendations

In regions where ENSO has less influence on rainfall pasture growth in the NT and WA:

1) Pasture growth should be analysed on a wet season rainfall basis, because this is more relevant to seasonal rainfall and pasture growth patterns than the period used for this study from the 1st of April to 31st of March which was chosen due to ENSO seasonal influences. For example, in longer wet seasons lasting through to April, the April rain will be attributed to the ENSO in the following year. This can cause odd outputs. For example in the eastern Barkly 100th percentile rainfall was 1340 mm and growth 4100kg/ha on an April to March basis, but 1200 mm and 3300kg/ha on a July to June period (Figure 1).

2) An analysis of the impact of additional climate drivers on pasture growth including IOD year types and IOD/ENSO combinations (Lim and Hendon 2017, Pepler *et al.* 2014) may provide further insights of relevance to northern beef producers.

Similar modelling for more of the Queensland and WA Climate Mate regions with relevant regional land type parameter sets would further increase capacity for extension and industry practice change.

Calibration of GRASP for WA land types or validation of relevant land types from the NT using WA field datasets is recommended to improve confidence in modelled pasture growth outputs in WA.

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8. Variability of Australian monsoon rainfall influenced by Pacific sea surface temperatures

Hanna Heidemann[1], Tim Cowan[1,2]
1 University of Southern Queensland, Toowoomba, Queensland, Australia
2 Bureau of Meteorology, Melbourne, Victoria, Australia

8.1 Background

The Australian monsoon (AUM) is a significant source of annual rainfall for tropical northern Australia, and usually occurs between December and March (DJFM; Holland 1986; Davidson et al., 1983). The interannual variability in AUM rainfall, and its association with different types of El Niño-Southern Oscillation (ENSO) events, such as those that occur in the Central (CP) or Eastern Pacific (EP), is not well understood on multidecadal timescales. In a region like northern Australia with its highly variable climate, agricultural and livestock communities require an understanding of decadal rainfall variability to help with better long-term decision-making.

Here we use observations to investigate unresolved issues regarding the influence of the Interdecadal Pacific Oscillation (IPO) and ENSO on AUM rainfall (Power et al. 1999; Meehl and Arblaster 2011), distinguishing between EP El Niño/La Niña and CP El Niño/La Niña events. In identifying the mechanisms behind AUM rainfall anomalies during selected events, we also explore the related large-scale atmospheric circulation and moisture fluxes through a composite approach.

8.2 Objectives

Provide new insights into decadal-scale variability of the interannual relationship between AUM rainfall and tropical Indo-Pacific sea surface temperature (SST) anomalies, to answer the question: How does the AUM rainfall response to CP and EP El Niño/La Niña events vary with the phase of the IPO?

8.3 Methodology

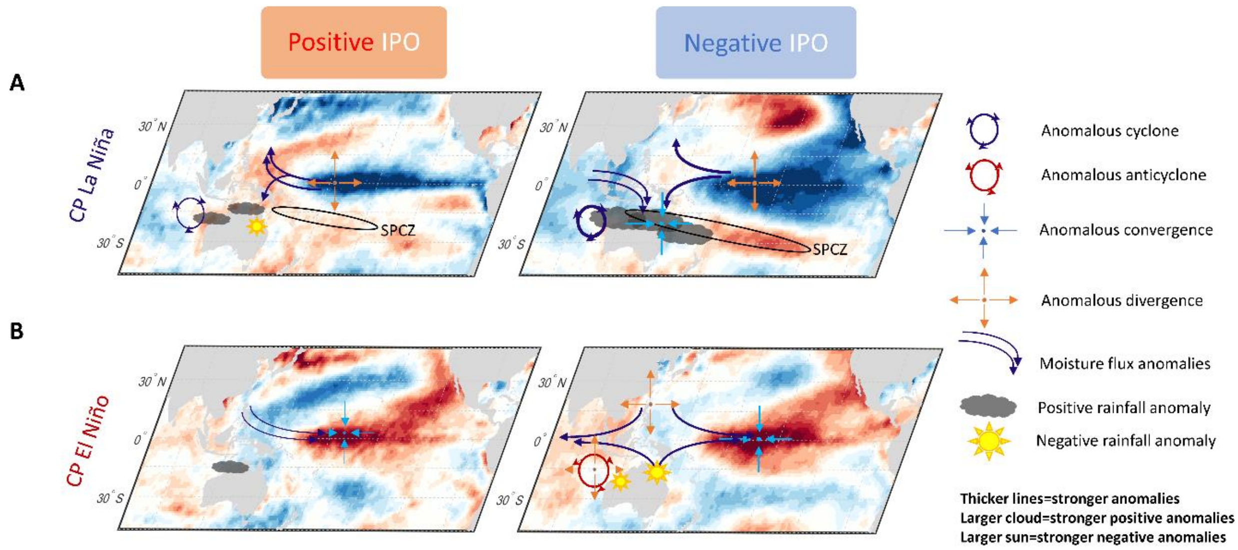
We assess observational data from 1920 to 2020, with a focus on Australian rainfall during the Australian monsoon season (DJFM). Gridded rainfall observations are evaluated using the Australian Water Availability Project (AWAP) dataset. We separate the analysis into the periods when the IPO was in a positive (1924-1944, 1977-1998) and negative (1945-1976, 1999-2014) phase. We analysed global mean sea level pressure, zonal and meridonal winds and specific humidity from the 20th Century Reanalysis version 3 dataset (Slivinski et al., 2019) from 1920 to 2015 to explain the causes for differences in rainfall patterns between IPO phases. Correlation coefficients were calculated and the statistical significance of composite atmospheric and oceanic anomaly maps determined through a Monte Carlo method (see Heidemann et al., (2022) for more details).

8.4 Results

During negative IPO phases, during which SSTs are cooler than usual in the eastern and central equatorial Pacific on a decadal timescale, CP El Niño events are associated with below-average rainfall over northeast Australia. In addition, an anomalous anticyclonic pattern is located to the northwest of Australia, and moisture is advected eastward towards the Dateline. In contrast, CP La

Niña events (distinct from EP La Niña events) during negative IPO phases drive significantly wet conditions over much of northern Australia, a strengthened Walker Circulation, and large-scale moisture flux convergence. During positive IPO phases, when SSTs are warmer than usual in the central and eastern equatorial Pacific, the impact of CP El Niño and CP La Niña events on AUM rainfall is weaker. Results are schematically summarised in Figure 1 (Heidemann et al., 2022). The influence of central Pacific SSTs on AUM rainfall has been stronger during the recent (post-1999) negative IPO phase. The extent to which this strengthening is associated with climate change or merely natural, internal variability is not known.

Figure 1: Schematic summarising Australia's DJFM monsoon rainfall anomalies and atmospheric features associated with CP La Niña (A) and CP El Niño (B) events during positive and negative IPO phases. Sea surface temperature anomalies are shown in the background of each panel. The approximate locations of anomalous atmospheric features, such as cyclones and anticyclones are indicated, as well as the direction of anomalous moisture fluxes and regions of moisture flux convergence and divergence.



8.5 Conclusion

8.5.1 Key findings

Negative IPO phases, during which SSTs are cooler than usual in the eastern and central equatorial Pacific on a decadal timescale, CP El Niño events are associated with below-average rainfall over northeast Australia.

CP La Niña events (distinct from EP La Niña events) during negative IPO phases drive significantly wet conditions over much of northern Australia

Positive IPO phases, when SSTs are warmer than usual in the central and eastern equatorial Pacific, the impact of CP El Niño and CP La Niña events on AUM rainfall is weaker.

8.5.2 Benefits to industry

An improved understanding of how rainfall varies on decadal and longer timescales over Australia will help decision making in agricultural industries, especially in grazing, due to an indication of rainfall availability that is associated with ENSO events or the potential for persistence of drought.

8.6 Future research and recommendations

A future study should investigate why there are large differences in Australian rainfall anomalies and atmospheric circulation between the positive and negative IPO phases during CP El Niño and La Niña events. This can be explored using numerical model simulations, which have the advantage of providing a longer timeseries of data to explore than the limited observational record.

8.7 References

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9. Drought Monitor

Laura Guillory, Thong Nguyen, Christa Pudmenzky, Jillian McCulloch, David Cobon
University of Southern Queensland, Toowoomba, Queensland, Australia

9.1 Background

The Australian Drought Monitor is an online tool that tracks the severity and spatial extent of drought conditions across Australia. It was designed to follow the lead of the U.S. Drought Monitor and the DPI Combined Drought Indicator for NSW, and to apply the benefits of multi-index drought monitoring techniques to the whole of Australia.

9.2 Objectives

Identify, review, develop and disseminate drought indices that meet the needs of northern Australia to identify periods of emerging drought risk in a timely manner, which are presented and updated in an appropriate spatial format online

Develop and disseminate a Drought Monitor that is used as a drought management tool for better drought planning and prediction for advisers, producers and policy makers.

9.3 Methodology

The Australian Combined Drought Indicator (CDI) is based on a combination of four different indices/indicators: Standard Precipitation Index (SPI), Soil Moisture (SM), Evapotranspiration (ET) and Normalised Difference Vegetation Index (NDVI). Each dataset is percentile ranked over a baseline period and the results combined using a weighted average, with the optimal weighting of the four indices determined by principal component analysis (PCA). The CDI has been calculated back to April 1998 when data for the NDVI began providing a hindcast of almost 22 years. The CDI is converted into categories ranging from the historically driest to wettest conditions and mapped. CDI maps are available at several rolling timescales including 1, 3, 6, 9, 12, 24 and 36 months and are published on the NACP website and updated monthly.

9.4 Results

9.4.1 A spatial representation of drought in Australia

The Drought Monitor is a robust drought monitoring prototype tool, delivered online on the NACP project website as an easy to interpret, colour-coded series of maps (https://nacp.org.au/drought_monitor). The website provides a continuous delivery of regularly scheduled monthly updates as new meteorological data is made available by SILO, the Copernicus Global Land Service, and the BoM. With each monthly update, maps for each available timescale are made available online. The CDI is customised for Australia's unique and varied climate, using PCA to determine the optimal weighting between input variables based on the climatological history of each cell location. It is available at a spatial resolution of 0.05° (~5 km) from April 1998 onwards. Samples of maps for all timescales, produced April 2021, can be seen in Figs. 1-2.

Figure 1. Final product of the Australian Combined Drought Indicator (CDI), featuring the 1-month CDI (CDI-1), 3-month CDI (CDI-3), 6-month CDI (CDI-6), 9-month CDI (CDI-9), 12-month CDI (CDI-12), 24-month CDI (CDI-24), and 36-month CDI (CDI-36).

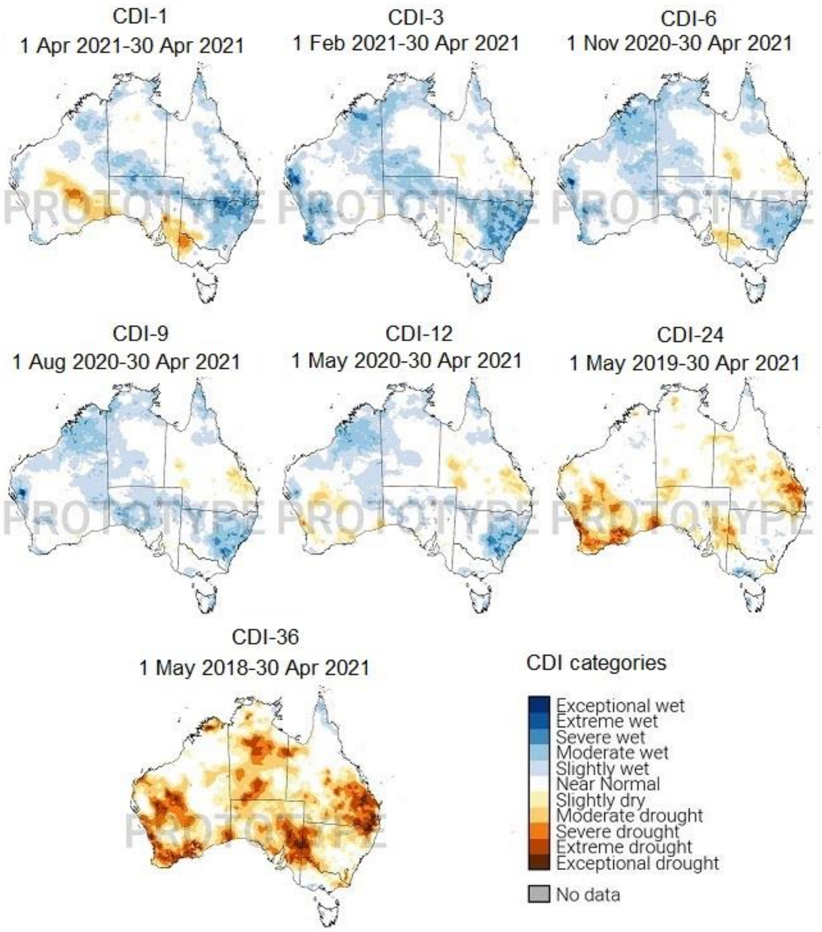
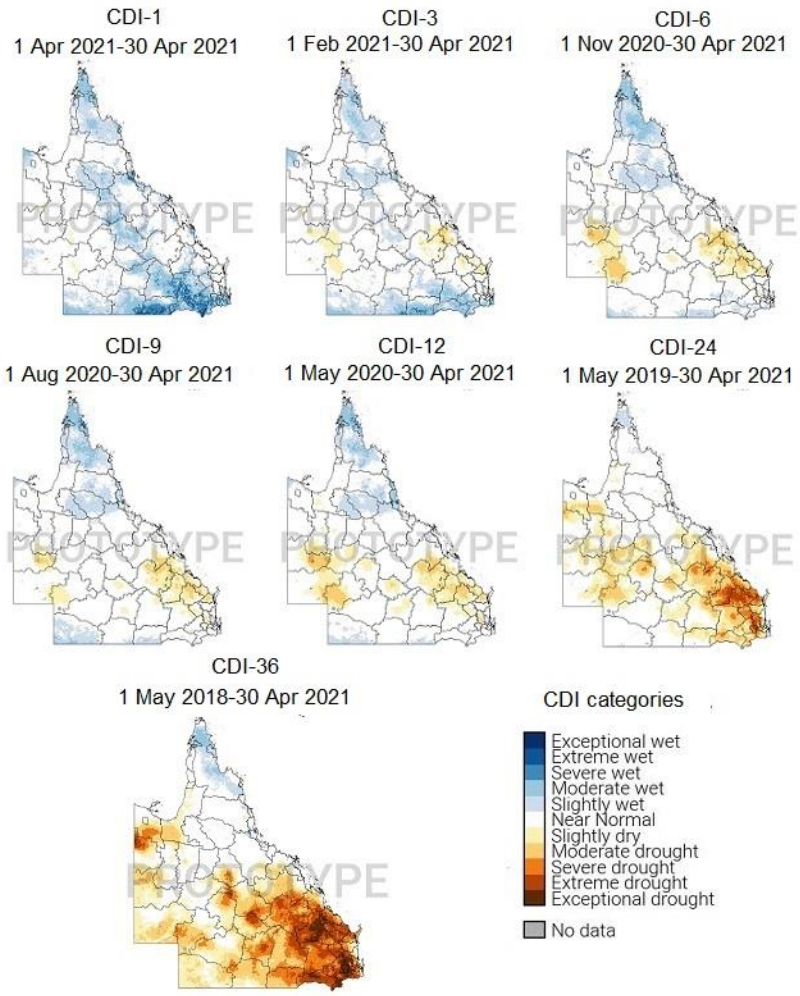


Figure 2. Final product of the Australian Combined Drought Indicator (CDI) extracted to show Queensland only, featuring the 1-month CDI (CDI-1), 3-month CDI (CDI-3), 6-month CDI-A (CDI-6), 9-month CDI (CDI-9), 12-month CDI (CDI-12), 24-month CDI (CDI-24), and 36-month CDI (CDI-36).



The categories for drought intensity were determined based on the US. Drought Monitor implementation (Svoboda et al., 2002). We defined a slightly dry period as conditions below the 30th percentile, a moderate drought as below the 20th percentile, a severe drought as below the 10th percentile, an extreme drought as below the 5th percentile, and an exceptional drought as below the 2nd percentile, as seen in Table 1.

Table 1. Australian Combined Drought Indicator (CDI) categories based on percentile rank values.

Value	*Category*
< 0.02	Exceptional Drought
0.02 – 0.05	Extreme Drought
0.05 – 0.1	Severe Drought
0.1 – 0.2	Moderate Drought
0.2 – 0.3	Slightly Dry

0.3 – 0.7	Near Normal
0.7 – 0.8	Slightly Wet
0.8 – 0.9	Moderate Wet
0.9 – 0.95	Severe Wet
0.95 – 0.98	Extreme Wet
> 0.98	Exceptional Wet

9.4.2 Ground-truthing via web survey

The Drought Monitor relies on field observations from extension officers, Climate Mates and local experts to provide feedback to "ground truth" observational data and corresponding indices. This is done through a monthly Drought Condition & Impact Report web-based survey to report on drought-related conditions and impacts in Australia. Participants are asked a range of multiple-choice questions reporting on crop and livestock production during a particular period (e.g. 1 month, 12 months) and how well the Drought Monitor map reflects the conditions in the local area.

At this stage 20 surveys have been conducted: 10 based on the 3-month CDI maps and 10 on the 12-months CDI maps. The results indicate that for the 3-month CDI, respondents indicated that the Drought Monitor was correct (answered "Well") 73% of the time, or close (answered "Well", "Slightly too wet", or "Slightly too dry") 92% of the time (Table 2). For the 12-month CDI, respondents indicated that the Drought Monitor was correct (answered "Well") 64% of the time, or close (answered "Well", "Slightly too wet", or "Slightly too dry") 94% of the time (Table 3).

Table 2. How well does the 3 months Drought Monitor map reflect the actual conditions according to the Drought Condition & Impact Report web-based survey.

Time Period	*Well*	*Well or Slightly too wet / dry*
Oct-2020	53%	89%
Nov-2020	50%	75%
Dec-2020	56%	81%
Jan-2021	56%	83%
Feb-2021	64%	100%
Mar-2021	100%	100%
Apr-2021	82%	88%
May-2021	82%	100%
Jun-2021	100%	100%
Jul-2021	83%	100%
Average	**73%**	**92%**

Table 3. How well does the 12 months Drought Monitor map reflect the actual conditions according to the Drought Condition & Impact Report web-based survey.

Time Period	*Well*	*Well or Slightly too wet / dry*
Oct-2020	68%	95%
Nov-2020	58%	83%
Dec-2020	63%	88%
Jan-2021	22%	78%
Feb-2021	75%	100%
Mar-2021	85%	100%
Apr-2021	56%	100%
May-2021	75%	100%
Jun-2021	82%	100%
Jul-2021	58%	92%
Average	**64%**	**94%**

9.4.3 Evaluation using wheat crop yield

Wheat yield data to evaluate the CDI were obtained from farm surveys conducted by the Australian Bureau of Agricultural and Resources Economics (ABARES), which provides a wide range of information on the performance of a number of sampled farms across the rural sector (ABARES, 2021, December).

The wheat yield (t/ha) data was linearly detrended to ignore the impact of other factors such as fertiliser and technology improvement. The results of correlation coefficients for each month from Apr to Dec across broadacre regions are represented in Figure 3. In general, a significant (at the level of 0.05) correlation between CDI and wheat yield are found during the mid-season (i.e., growth and development season) from Jul to Nov.

9.4.4 Evaluation using modelled pasture growth

Modelled pasture growth from AussieGRASS was compared to the CDI for 3- and 12-month periods. The 12-month correlations were strong for most of Australia (Figure 4) but were weakest in Cape York and the Top End. The 3-month correlations were strong for large parts of Australia (Figure 5) in spring, summer and autumn. In summer, autumn and winter correlations in the Top End were low or negative. It is unclear if this is due to the CDI or lack of parameterisation of the pasture growth model in these regions.

Figure 3. Correlation coefficients between Australian Combined Drought Indicator (CDI) and detrended wheat yield over the period 1999-2020.

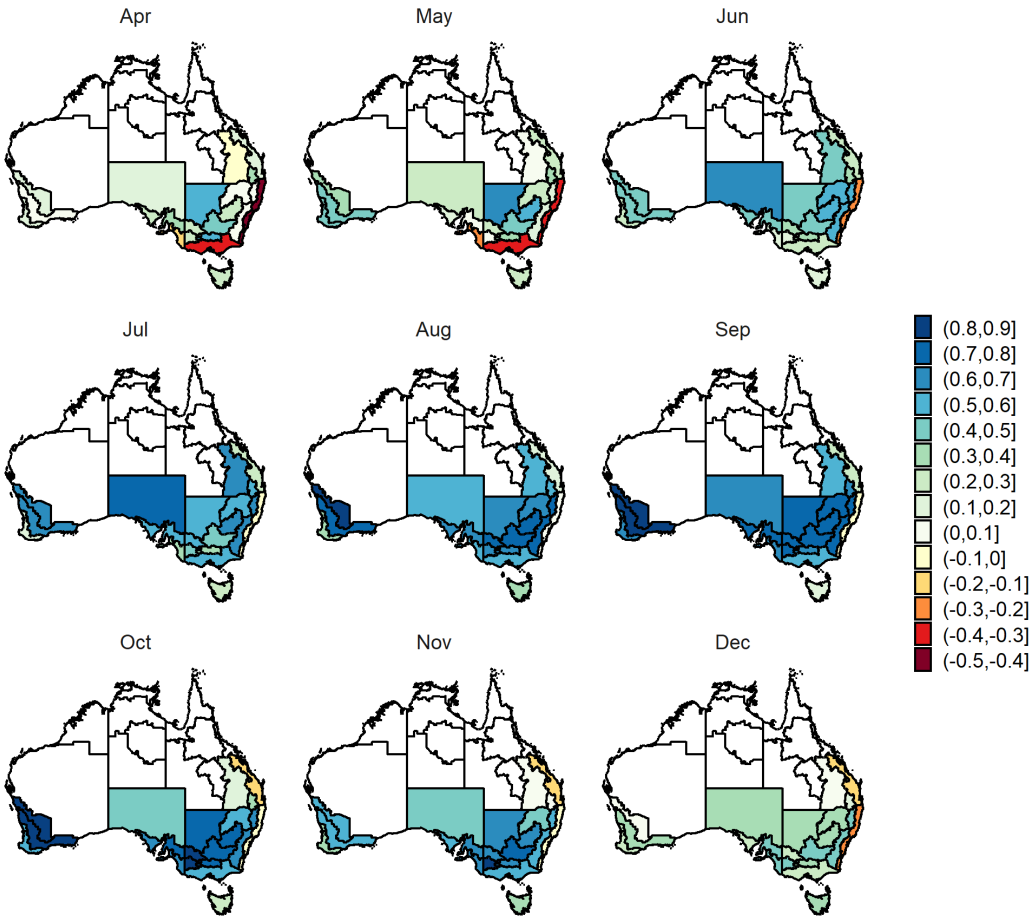


Figure 4: Correlation coefficient between 12-month CDI and 12-month total pasture growth (kg DM/ha) over the period 1999-2019

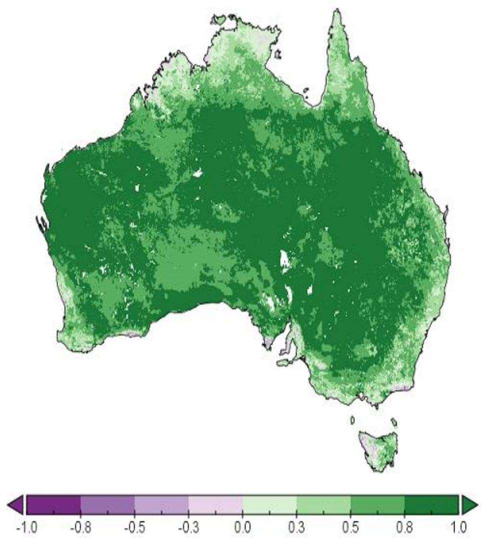
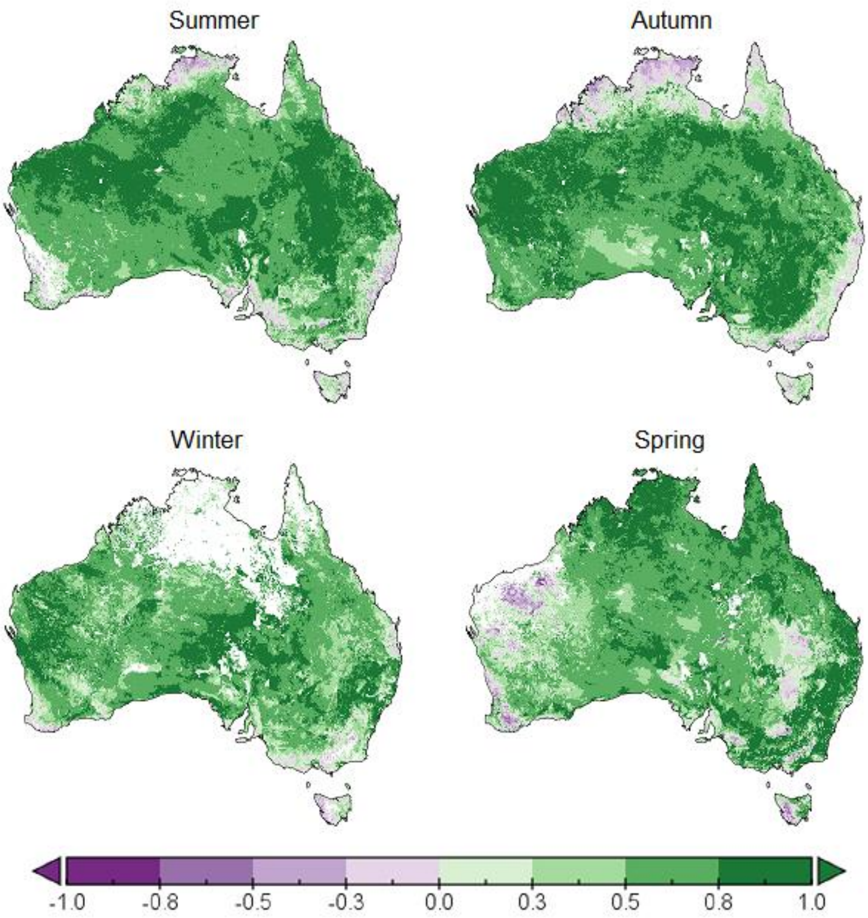


Figure 5: Correlation coefficient between 3-month CDI and 3-month total pasture growth (kg DM/ha) over the period 1999-2019



9.5 Conclusion

9.5.1 Key findings

The Drought Monitor is an online drought management tool that identifies drought risks across Australia.

Evaluation demonstrated that the tool was well received by users, and that the data was significantly correlated with wheat yield.

9.5.2 Benefits to industry

The 4 indices CDI covers meteorological and agricultural drought

The CDI is an objective drought assessment tool used by the Queensland government local drought committees to help declare and revoke drought.

9.6 Future Research and recommendations

There are avenues for potential future development, such as revisiting the selection of input data as more remotely sensed options become available in Australia, which will increase the accuracy of the

Drought Monitor in rural areas where weather stations are sparse. In future iterations, the Drought Monitor may be simplified, and timescales condensed down to three options, representing short, medium and long-term impacts which can make the tool more easily accessible to producers.

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10. Drought Outlook

Thong Nguyen[1], Laura Guillory[1], David Cobon[1], Matthew Wheeler[2], Debra Hudson[2]
1 University of Southern Queensland, Toowoomba, Queensland, Australia
2 Bureau of Meteorology, Melbourne, Victoria, Australia

10.1 Background

Two operational drought forecast tools are currently available on-line; these are (i) the US Drought Outlook (available as monthly and seasonal/3-month drought forecasts) produced by the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) and available through the National Integrated Drought Information System (NIDIS); and (ii) the World Bank Global Forecast Drought Tool developed by the International Research Institute for Climate and Society (IRI) at Columbia University, in collaboration with the CPC and University of Maine.

The US Monthly and Seasonal Drought Outlooks, presented as forecast maps, are developed by merging data from a number of sources: CPC temperature and precipitation outlooks; long lead forecasts such as the National Centres for Environmental Prediction (NCEP) Climate Forecast System (CFS) and the North American Multi-Model Ensemble (NMME) system; short-term weather forecasts from NCEP and ECMWF; and current conditions from the US Drought Monitor.

The World Bank Global Forecast Drought Tool, presented as global/regional forecast drought severity and drought risk maps, provides probabilistic forecasts of future Standardised Precipitation Index (SPI) as an indicator of drought for a range of accumulation periods (3, 6, 9 or 12 months) based on monthly precipitation predictions from multiple NMME models and initial observed SPI conditions.

10.2 Objective

To develop a prototype drought outlook tool for northern Australia based on the simplified drought forecasting approach of IRI's World Bank Global Forecast Drought Tool, using the Combined Drought Index (CDI) in conjunction with ACCESS-S model SCF/precipitation forecasts.

10.3 Methodology

The Drought Monitor was used as an indicator of the observed drought conditions to which precipitation forecasts were applied to produce a forecast of drought (Drought Outlook). The Drought Outlook is produced by considering current drought conditions, as represented by the CDI categories, and how the future CDI is likely to be affected by seasonal precipitation forecasts. The Drought Outlook will indicate that a region is likely to enter drought if it receives an extremely low precipitation forecast. If that region is already in drought, then the Drought Outlook will indicate that the drought is likely to intensify. In the event of a high precipitation forecast, the Drought Outlook will indicate that drought conditions will improve In the case of a less severe drought, such a precipitation forecast may indicate that the drought will end. The full list of Drought Outlook categories is shown in Table 1.

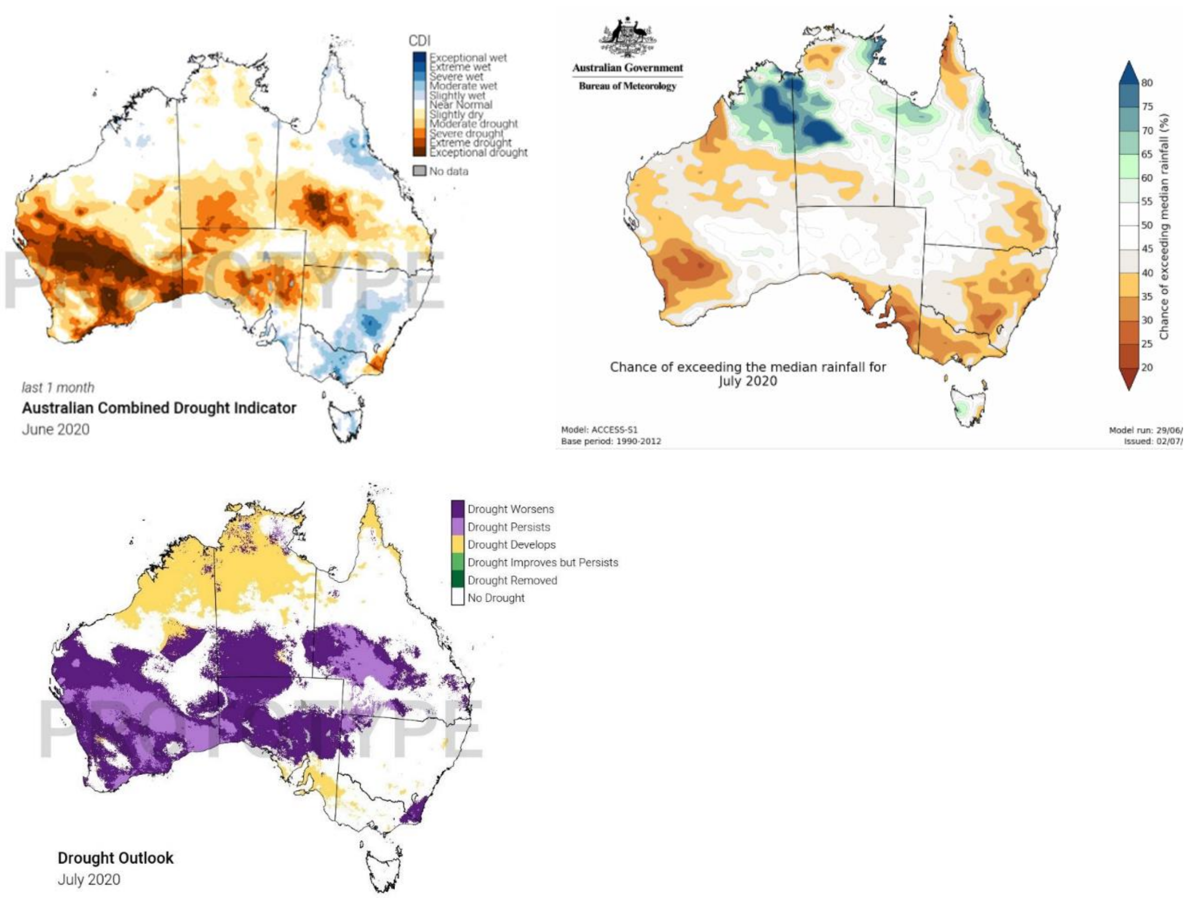
Table 1 – A description of forecast categories used by the Drought Outlook and how they relate to the CDI categories

Category	Description	Relation to CDI
Drought Worsens	Drought is currently observed in the area, and is expected to intensify	A current CDI category of Moderate Drought or worse, with an expectation that the category will become Severe Drought or worse.

Drought Persists	Drought is currently observed in the area, and is expected to continue	The current CDI category will remain the same (Moderate Drought or worse only)
Drought Develops	There is no drought currently observed in the area. Drought is expected to develop in the area.	A current CDI category of Abnormally Dry or better, with an expectation that the category will become Moderate Drought or worse
Drought Improves but Persists	Drought is currently observed in the area. The drought is expected to improve, however the area may still be classified as being in drought.	A current CDI category of Severe Drought or worse, with an expectation that the category will become less severe while remaining in drought
Drought Removed	Drought is currently observed in the area, and is expected to be removed.	A current CDI category of Moderate Drought or worse, with an expectation that the category will become Abnormally Dry or better
No Drought	There is no drought currently observed in the area, and drought is not expected to develop.	A current CDI category of Abnormally Dry or better, with an expectation that the category will not become Moderate Drought or worse

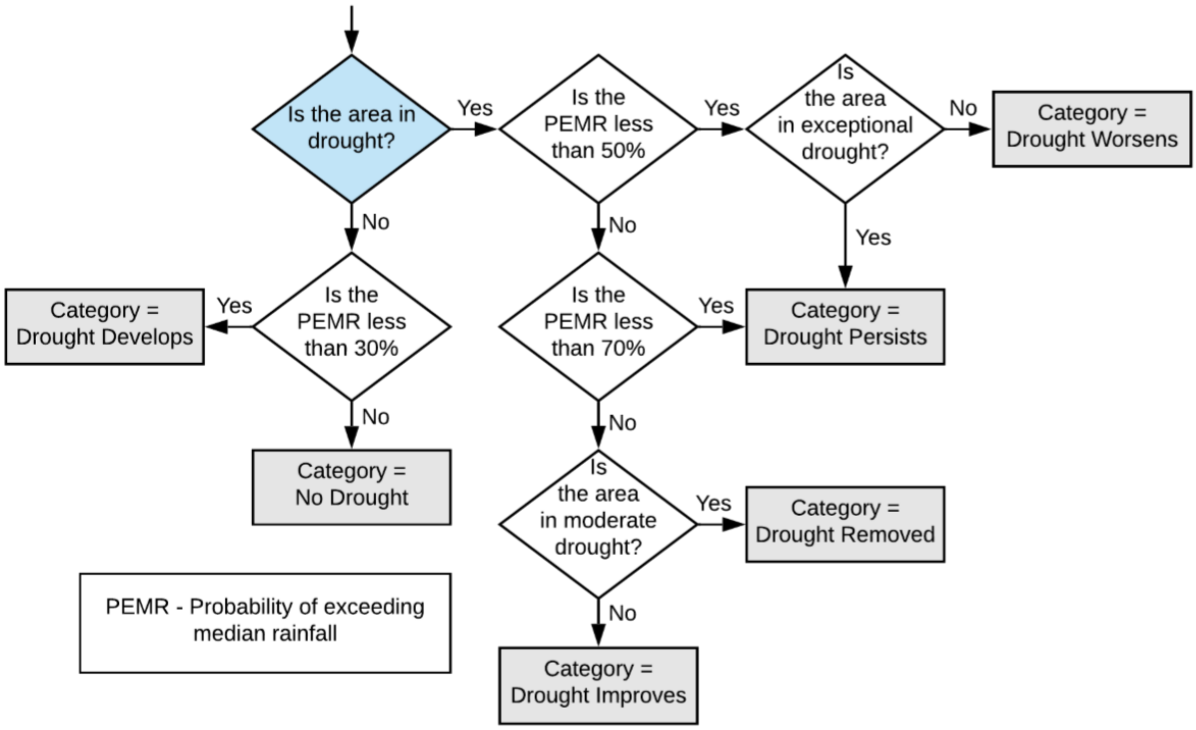
Both weekly and seasonal forecasts from ACCESS S1 are used to produce different Drought Outlook prototypes. The data provided is in the form of the probability of exceeding the median rainfall, as shown in Figure 1.

Figure 1: a) CDI June 2020 b) Rainfall forecast from the Bureau of Meteorology: chance of exceeding median rainfall for July 2020 c) Drought Outlook July 2020



The probability of exceeding the median rainfall (abbreviated to PEMR in Figure 2) is compared to a set of thresholds to determine likely future impacts on drought. A set of rules, illustrated in the decision flow chart in Figure 3, are used to combine the current drought conditions and the PEMR to determine the forecast category.

Figure 2 – Decision flow chart showing the rules used to determine the drought forecast category for the Drought Outlook



10.4 Results

10.4.1 Drought Outlook Prototypes

Drought Outlook prototypes have been produced. The first is a one-month forecast which is based on the one-month precipitation forecast (shown in Figure 3), and the second is a three-month forecast which is based on the seasonal precipitation forecast (shown in Figure 4).

Realtime prototypes have been in production since November 2019. Hindcasts have also been produced from March 1998 to December 2012, a length of record restricted by availability of ACCESS S1 hindcasts for probability of exceeding median rainfall.

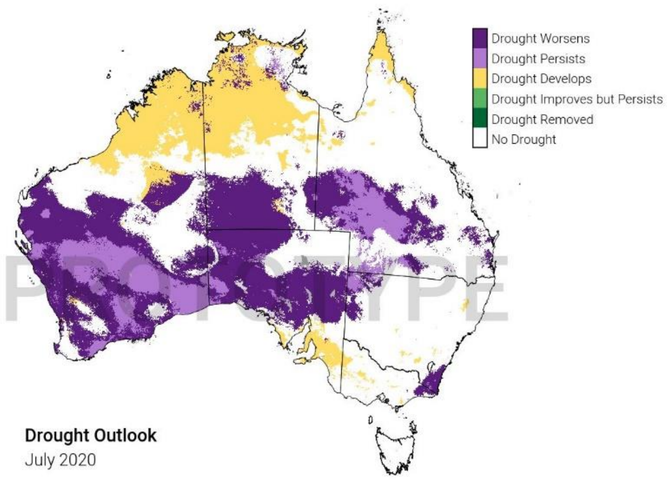


Figure 3 – A one-month Drought Outlook prototype for July 2020

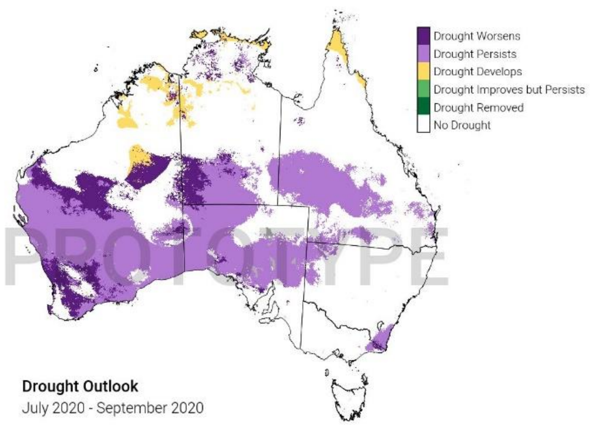


Figure 4 – A three-month (seasonal) Drought Outlook prototype for July-September 2020.

10.4.2 Evaluation

Drought Outlook evaluation was performed by computing the percent consistent, a value that refers to the percentage of drought forecasts (drought outlook) that was consistent with the CDI category later observed i.e., the number of consistent forecasts for a category divided by the total number of forecasts made for that category. The CDI category includes (1) Exceptional Drought, (2) Extreme Drought, (3) Severe Drought, (4) Moderate Drought, (5) Abnormally Dry, (6) Near Normal, (7) Abnormally Wet, (8) Moderate Wet, (9) Severe Wet, (10) Extreme Wet, and (11) Drought Worsens. The consistent is defined as follow:

- Outlook is "No Drought" or "Drought Removed" and the later CDI is not in any drought category (i.e. $CDI_{later} \geq (5)$);
- Outlook is "Drought Improves" and $CDI_{previous} < CDI_{later} < (5)$;
- Outlook is "Drought Develops" and $CDI_{later} < (5) \leq CDI_{previous}$;
- Outlook is "Drought Persists" and CDIlater = CDIprevious < (5);
- Outlook is "Drought Worsens" and CDIlater = CDIprevious < (5).

Other cases are counted as inconsistent forecasts. For example, using hindcast data for the 14-year period,04/1998–12/2012, if 11 of the 14 drought outlooks for Jan-Mar for a grid cell are consistent with the observed CDI, the percent consistent value at that cell will be 79%. Figures 5 and 6 show the percent consistent of 1- and 3-month Outlooks.

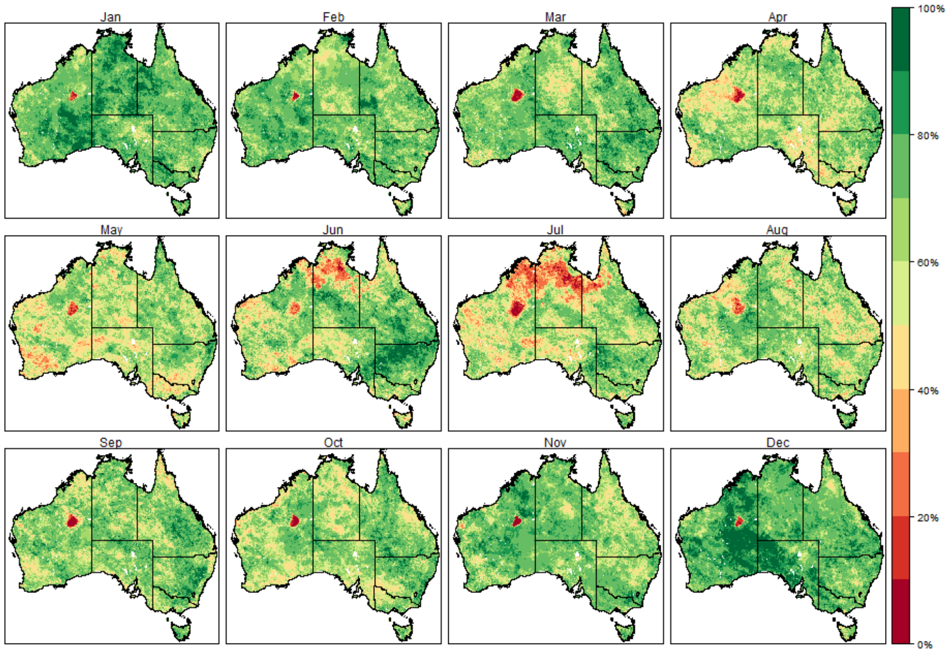


Figure 5 - Percent consistent of 1-month outlook.

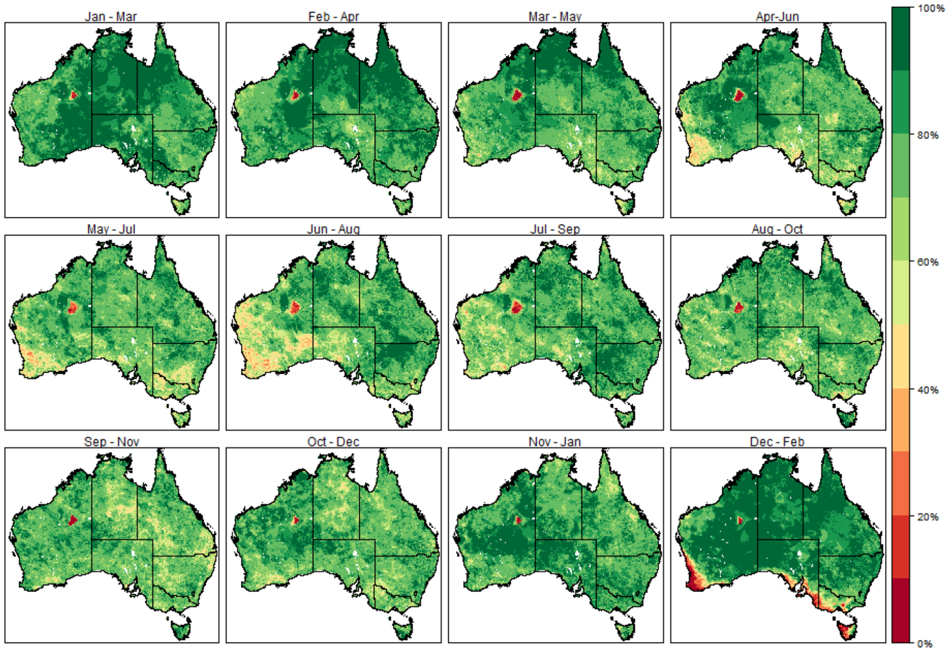


Figure 6 - Percent consistent of 3-month outlook.

10.5 Conclusion

10.5.1 Key findings

The Drought Outlook prototypes currently available offer a preliminary look at potential drought forecasting tools for Australia, available in 1-month and 3-month versions. It is currently being withheld from production until further testing, evaluation, and validation has been completed. It has been through a number of prototypes with changes made to categories, thresholds, rules and colours (Appendix 1) to help improve its usefulness and practical application The Drought Outlook hindcast is currently available from May 1992 to January 2022.

10.5.2 Benefits to industry

Predicting how drought conditions will change over months and seasons will assist the industry with making informed management decisions.

10.6 Future research and recommendations

Further validation of the Drought Outlook

Use of Vegetation Health Index for validation

Skill testing of the Drought Outlook

11 Northern Rainfall Onset

Tim Cowan[12], Matthew Wheeler[2]
1 University of Southern Queensland, Toowoomba, Queensland, Australia
2 Bureau of Meteorology, Melbourne, Victoria, Australia

11.1 Background

The Northern Rainfall Onset (NRO) is the date at each location when 50 mm of accumulated rainfall is received from 1 September (Lo et al. 2007) each year. It is a proxy date for the useful pasture growth that is stimulated by showers and increased storm activity during the build-up towards the peak monsoon months of January and February. From 2015 (i.e., before NACP2), the BoM began providing forecasts of the probability that the NRO will be later or earlier than usual, using their low-resolution (250 km grid) coupled seasonal prediction system POAMA2 (Drosdowsky and Wheeler 2014). The forecasts were released three times per year in June, July and August. In August 2018, as NACP2 was beginning, the BoM upgraded to a new seasonal prediction system, ACCESS-S1 (Hudson et al. 2017). However, the BoM did not have any allocated resources to transfer the NRO forecasts to the new system.

Given the importance of the NRO for the northern Australian grazing industry, NACP2, therefore, contributed to transferring the NRO forecast product to ACCESS-S1 and evaluating its skill. Improvements to the observed "normal" onset and the timeliness and frequency of NRO forecasts were also made through NACP2.

11.2 Objectives

Provide an ongoing and improved NRO forecast product through the BoM website at http://www.bom.gov.au/climate/rainfall-onset/

11.3 Methodology

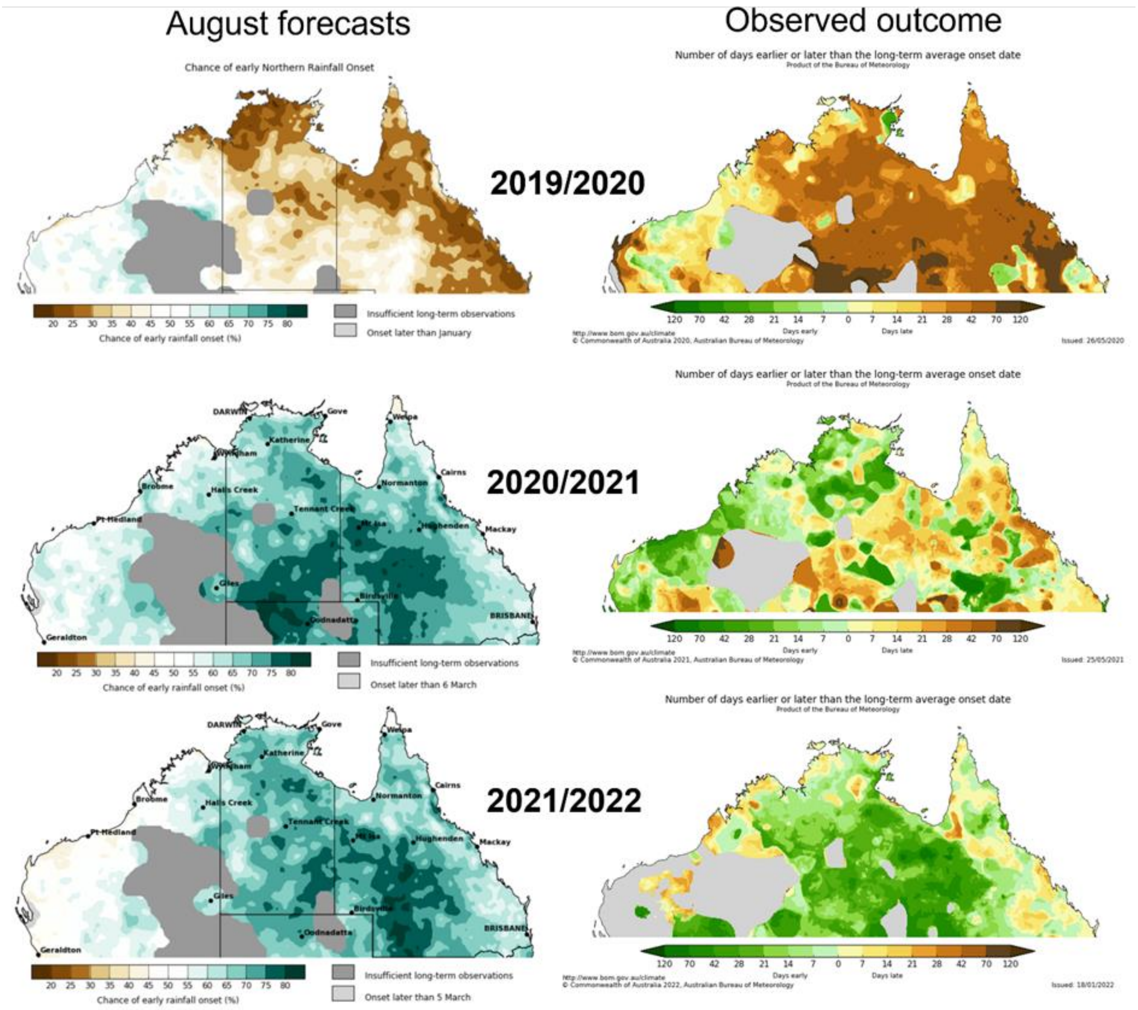
The observations used for updating the "normal" onset date (previously 1960-2009, now 1960-2012) were the 5km gridded rainfall from the Australian Water Availability Project (AWAP; Jones et al. 2009). The same observations were used for verification. To determine the best method for forecasting the NRO in ACCESS-S1, comparisons were made between the raw, bias-corrected, and calibrated outputs (see de Burgh-Day et al. 2020 for more details on the calibration process) using hindcasts over the period 1990-2012, initialised on the 1st, 9th, 17th, and 25th of the month between 1 May and 1 September. With only 11 ensemble members per start date, we combined three consecutive start dates to create 33-member ensembles. The prediction skill was assessed using the Brier Skill Score compared to climatology, with anything over 10% deemed "significant". The observed NRO median and all hindcast probabilities were smoothed 50 times using a 1-2-1 spatial filter to reduce local noise. Further details are published in Cowan et al. (2020).

11.4 Results

For the ACCESS-S1 hindcast skill, we found that the calibrated outputs performed better than the raw and bias-corrected hindcasts. For combined June start dates (9th, 17th, 25th), about 36% of northern Australia showed a "significant" improvement in skill compared to 13% for the bias-corrected. For the combined August start dates, the calibrated ensemble showed a significant improvement over 54% of northern Australia compared to 21% for the bias-corrected ensemble. These results are summarised in Cowan et al. (2020) with published skill maps on the internal NACP Research Project page for stakeholders. An initial assessment of ACCESS-S1's replacement forecast system, ACCESS-S2, shows that it is at least equal or marginally better than S1 in terms of hindcast skill. The greatest improvements are seen over the Pilbara-Gascoyne basin, likely stemming from the longer hindcast lead times in S2 (~9 months compared to ~6.5 months in S1). As a result of this NACP2 research, the first official NRO forecast from ACCESS-S1 was released in July 2019, and the first from ACCESS-S2 will be released in late June 2022.

Verification of the NRO forecasts released in 2019, 2020, and 2021 (i.e., during NACP2) is provided in Figure 1. The 2019 forecast was for a low probability of early onset in almost all locations, which verified very well. The 2020 forecast suggested a high probability of early onset, which verified well in most locations, except for the northeast. The latter failure was likely due to the overprediction of the warm waters to the north of Australia and the underprediction of the Madden Julian Oscillation in November (Lim et al., 2021). This current year's forecast (2021/22) has again been seen as widely successful (Figure 1, bottom row), particularly across central inland regions.

Figure 1: (left) Official BoM August forecasts from ACCESS-S1 showing the chance of an early NRO for (top) 2019/20, (middle) 2020/21 and (bottom) 2021/22. (right) Corresponding observed outcome showing the number of days earlier (green) or later (brown) than the long-term median observed NRO. Grey patches in the forecasts indicate where there are insufficient observations to be able to calibrate the model. The same applies to the observations; however, in the far west for 2021/2022, the grey colour also shows regions that have yet to reach their NRO at the time of writing (January 2022).



11.5 Conclusion

11.5.1 Key findings

Predicting the NRO for June and August start dates was significantly improved using the calibrated outputs derived from NACP research

11.5.2 Benefits to industry

The NRO product benefits the grazing industry, among other industries, by giving about 1-3 months warning of the likely chances of an early or late start to useful pasture-growing rain. Without NACP2, the provision of NRO forecasts from the BoM would have very likely ceased in 2018 when the shift to ACCESS-S1 was made. NACP2, therefore, allowed this industry-relevant product to continue and be improved in the following ways:

- More skilful, with documented improvements from POAMA2 to ACCESS-S1 to ACCESS-S2.
- Timelier: ACCESS-S2 outputs are provided about two days earlier than S1.
- More frequent: NRO forecasts were issued five times in 2021 compared with 3 in 2015-2019.
- More detailed through higher spatial resolution and expanded range into southern QLD.
- A more realistic "normal" date using an updated climatology.

11.6 Future research and recommendations

We recommend the following:

- That the USQ-BoM collaboration continue to maintain and improve the NRO forecast product into the future.
- That greater clarification be made between the NRO and Green Date.
- A similar methodology could be applied to a Green Date forecast product.

11.7 References

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12 Rainfall Bursts

Tim Cowan[12], Matthew Wheeler[2]
1 University of Southern Queensland, Toowoomba, Queensland, Australia
2 Bureau of Meteorology, Melbourne, Victoria, Australia

12.1 Background

To support short-term planning decisions, pastoralists often need to know the chance of meaningful rainfall in the upcoming weeks (e.g., 50 mm in 3 days; Balston and English, 2009). Prior to NACP2, the only forecast products available to producers were 7-day deterministic forecasts and monthly/seasonal predictions. In mid-2020, the Bureau of Meteorology (BoM) started providing multi-week forecasts of rainfall and temperature, yet little information was available on the likelihood of multi-day (or meaningful) rainfall events. Hence, NACP2 researchers, with support from the Climate Mates, were tasked to develop a meaningful rainfall metric that producers could use to help with decisions around such things as feed budgeting, moving stock, and planned burns. This led to the development of the rainfall burst prototype forecast product.

Rainfall bursts are short-lived phenomena where rain occurs over consecutive days. They are common over northern Australia, particularly during the monsoon months between December to March. These multi-day bursts are often associated with the active pulse of the Madden-Julian Oscillation (MJO; Wheeler and McBride, 2012), but can also be influenced by midlatitude processes (Narsey et al., 2017). In the development of a rainfall burst forecast product, we had to ensure that the prototype was easy to understand by our customers and fit for different purposes. Our targeted demographic were northern beef producers; however, we were aware that other industries like cropping would be interested in a rainfall burst product (Mollah and Cook, 1996).

12.2 Objectives

The main objective here was to design, develop and release a prototype rainfall burst product. A secondary objective was to document the product development process and burst skill in the BoM's forecast model (Cowan, Wheeler, Hudson, et al., 2022; Cowan, Wheeler, Sharmila, et al., 2022). Other objectives included providing the Climate Mates with virtual training on the product and more broadly promote the product to end-users. All objectives were achieved, and due to the popularity of the product, it was selected to be made operational by the BoM with a mid-2022 release date.

12.3 Methodology

The burst product development commenced in early 2019, with the first prototype products developed in September 2020. After discussions with the Climate Mates, it was decided that a burst would be defined as an accumulation of meaningful rain over a 3-day period, with the thresholds set to 20 mm, 30 mm, 50 mm and 70 mm. The reasons for choosing four thresholds stem from the fact that low thresholds are more suited for drier light/sandy soil regions like the Pilbara, compared to climatologically wetter regions like far northeast Queensland. Originally, the burst definition included a minimum threshold of 2 mm/day in at least 2 out of the 3-days; however, after discussions between BoM researchers and the Climate Mates, it was decided that there would be no minimum amount per day. An example of a 30 mm in 3-day burst is given in Table 1 of Cowan, Wheeler, Sharmila, et al., (2022).

Two prototype burst products were initially created: (1) burst day potential defined as the likelihood of a burst event starting in the forecast period; and (2) number of burst days defined as the model ensemble median (out of 99-members) number of burst days in the forecast period. After consultation with the Climate Mates, it was decided that product (2) should be discontinued due to the confusing nature of the definition of a burst event versus burst days. For the four thresholds, bursts were determined from observations using the 5 km AGCD data (Australian Bureau of Meteorology, 2019) for the period 1960-2018, and for hindcasts from ACCESS-S1, between October and April for the 1990-2012 period. Following the release of ACCESS-S2, bursts were determined across its hindcast period 1981-2018 (as well as the common period shared with ACCESS-S1). Hindcast skill was assessed in two ways, firstly through the Brier Skill Score, using combined start dates across the summer season; and secondly, using the Symmetric Extremal Dependence Index (SEDI) – the latter being a better approach for evaluating rare events (Marshall, Hendon and Hudson, 2021). For brevity, we focus on the latter metric in this report. An evaluation of skill in ACCESS-S1 using the Brier Skill Score with results compiled across the summer monsoon season are detailed in Cowan, Wheeler, Sharmila, et al. (2022). Further details on assessing skill using the SEDI score is shown in Cowan, Wheeler, Hudson, et al. (2022).

12.4 Results

12.4.1 Observed burst activity

The first burst (referring to a 30 mm in 3-day event) of the wet season typically arrives over Darwin and the western Top End in late November, although La Niña conditions are associated with earlier (late October) bursts. The further inland and away from the coast, the later the onset of burst activity except for the Pilbara where a late February first burst is commonplace even near the coast. The final burst of the wet season (i.e., prior to May) generally occurs in April. More information on the relationship between El Niño, La Niña and onset/retreat dates of burst activity is provided in Cowan, Wheeler, Sharmila, *et al.* (2022).

Long-term trends in burst activity are hard to evaluate, given the subjective threshold definition, and the fact that an increase in burst activity in one month might be offset by a decline in another month. Trends in burst activity were assessed for the four thresholds over two grid point locations representing Gregory Downs in QLD's Gulf region and Dampier Downs in the far northwest. While there were no significant trends in monthly burst activity for Gregory Downs, Dampier Downs (and the broader northwest) now experiences more December burst days compared to the 1960s (a significant increase > 3 days in 58 years). This is consistent with an increasing summer rainfall trend over the northwest since the 1950s and earlier dates of the northern rainfall onset (Drosdowsky and Wheeler, 2014). Trends in ACCESS-S1 were not assessed due to the insufficient hindcast length.

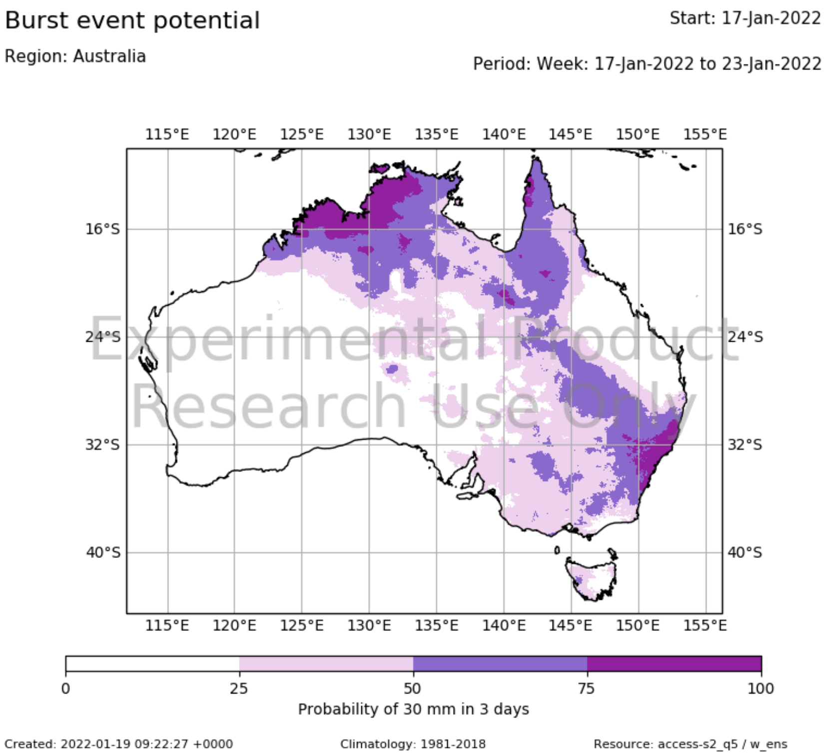
12.4.2 Biases in ACCESS-S1

The biases and skill in burst metrics were evaluated for the first start dates of December to March (DJFM) for the raw and calibrated hindcasts of ACCESS-S1 over 1990-2012. Biases were determined as the difference between the hindcast ensemble DFJM mean (23 years $\times$ 4 months $\times$ 11 members) and the AGCD observations. We focus only on 30 mm in 3-day bursts. The uncalibrated hindcast ensemble simulates too many summer burst days over most of northern Australia, aside from the Kimberley and along the far northeast coastline, as well as longer bursts than are observed. In spite of this, weaker magnitude burst events are simulated by ACCESS-S1 along all of the tropical north, except for the inland Gulf, while ACCESS-S1 overestimates the amount of rain falling from isolated, non-burst events. Calibrating the hindcasts to observations reduces the biases in burst day frequency, and slightly reduces the average duration biases, however it does little to alleviate the magnitude biases (see Figure 4 of Cowan, Wheeler, Sharmila, *et al.* (2022)). Hence it appears that the daily calibrations partially corrects ACCESS-S1's light and heavy rainfall distributions, however this leads to some over-correction (i.e., change of sign in the bias).

12.4.3 Skill in ACCESS-S1 and ACCESS-S2

In assessing the prediction skill, we compared ACCESS-S1 and S2's ability to predict a burst event starting in the forecast period, known as the burst potential. An example of the burst potential product is shown in ***Figure 7*** for a 30 mm in 3-day event. This is what is currently available to experimental users on the NACP Forecast Visualisation Tool, introduced for the 2020/21 northern wet season. The forecast map shows a high (> 75%) likelihood of a burst event occurring from Darwin across to the Kimberley coast. Away from the tropical north, and into the rangelands, the probability drops to between 50-75%.

Figure 7: Example of the burst event potential product. Shown above is a likelihood of a 30 mm in 3-day burst event over 17-23 January 2022 from a 17 January 2022 start date (e.g., lead week 0 forecast). This forecast product is available to NACP clients via the NACP Forecast Visualisation Tool.



For this time of year (mid-January), the western Top End and Cape York would normally experience a high (75-100%) chance of a burst event, based on the long-term observed climatology. The probability drops away to between 25 and 50% over the central NT and QLD's Gulf region. Therefore, given the forecast in ***Figure 7*** shows strong probabilities, this should imply greater confidence in the forecast, and this particular forecast verified well.

We compared hindcast skill between ACCESS-S1 and S2 using the common period: 1990-2012, and combined start dates for the 1st and 16th/17th of each month separately from December to March (e.g., 1/16[17] Dec, 1/16[17] Jan, etc. for ACCESS-S1[S2]). Maps of the SEDI skill score (not shown), indicate skill in burst prediction drops away after lead week 0, and hovers just above zero for December and January forecasts by lead week 3. Prediction of rarer burst events (e.g., 50 and 70 mm thresholds) is less skilful than weaker magnitude burst events, while perhaps more importantly, the skill in ACCESS-S2 is, on the whole, slightly better than ACCESS-S1 across the majority of start dates and lead times. This also holds true for northwest Australia (Cowan, Wheeler, Hudson, *et al.*, 2022).

12.5 Conclusion

12.5.1 Key findings

- The burst potential prototype was successfully released on the internal NACP forecast visualisation tool in November 2020.
- A research paper explaining the burst skill in BoM's seasonal forecast model (from 2018-2021), ACCESS-S1, was published in December 2021 (Cowan, Wheeler, Sharmila, *et al.*, 2022). A further report is currently in preparation (Cowan, Wheeler, Hudson, *et al.*, 2022).
- The burst product was presented to beef producers at Beef2021, which garnered local press coverage in QLD Country Life[1] and Grain Central[2].
- The BoM's seasonal forecast system (from 2018-2021), ACCESS-S1, is able to predict burst activity with reasonable skill out to three weeks.
- The newest forecast system, ACCESS-S2, shows greater skill than S1 across all lead weeks in December to March (Cowan, Wheeler, Hudson, *et al.*, 2022).

16.3.2 Benefits to industry

The burst event potential was selected to be released operationally by the BoM (for May 2022), and hence, becomes the first NACP2 prototype product to be developed and converted to an official product. From this, a set of observed climatology and model skill maps were developed, helping experimental users of the prototype in their interpretation of the forecasts. In terms of benefits to the beef industry, based around discussions with the Climate Mates, it has been suggested that the burst product will help with decisions around:

- Exporting/trucking out cattle from properties (i.e., access to roads if wet).
- Feed budgeting during the wet season.
- Moving cattle to safety before high-risk events.
- Weed spraying.
- Cropping enterprises (hay collection before event).
- Green Date and stock numbers.

There are also advantages to using the burst product is other agricultural industries. For example, the WA grains sector depend on meaningful rainfall to determine their autumn break/onset at 15-20 mm in 3-days and then 5 mm over 3-days from early June for good harvest outcomes (Kerr and Abrecht, 1992). In the far northern tropics, a burst product with a 50 mm threshold would be of use

[1] https://www.queenslandcountrylife.com.au/story/7229535/new-scientific-rainfall-tool-set-to-predict-rain-bursts/

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

in planning legume pasture sowing in early December, while lower thresholds (~10 mm) are of use at the end of the monsoon season (March) because late wet season rain can impact the quality of the ripening grain (Mollah and Cook, 1996).

In the near future, there is a plan to produce a short professionally made video on the burst product, targeted towards the northern beef industry. This will coincide with the operational release of the product and cover how to read the burst forecast and interpret the forecast accuracy.

12.6 Future research and recommendations

The key challenge of this research was incorporating the needs of the customers into the product development. An early version of the product was presented to the Climate Mates in September 2020, with feedback returned from five. The challenge was then to embed the suggested changes in the feedback, without compromising the product's integrity. This process highlighted the importance of clarity, conciseness, and transparency during product development, keeping in mind the customers' needs, not just science behind the product. In future, we aim to refine the process of responding to producer feedback, to make it easier to incorporate suggestions and improvements.

Future R&D will focus on refining the burst product by incorporating pasture growth (which is regionally diverse across northern Australia based on climate and soil type), akin to a Green Date burst product, as opposed to relying entirely on arbitrary rainfall thresholds. Also, there should be a greater focus on "breaks" during the monsoon, referring to dry spells in the monsoon season. The plan is to investigate monsoon "breaks" and what controls false green dates (i.e., early wet season rainfall events, followed by extended dry spells) with the help of the Climate Mates.

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13 Using green dates for managing and budgeting pasture

Damien O'Sullivan[1], Chelsea Jarvis[2], David Cobon[2]
1 Department of Agriculture and Fisheries, Kingaroy, Queensland, Australia
2 University of Southern Queensland, Toowoomba, Queensland, Australia

13.1 Background

The NACP aims to improve the knowledge and skills of producers across grazing industries to support proactive management of climate variability which minimises exposure to environmental, profitability, and productivity losses due to drought or drier than normal wet seasons and maximises opportunities presented in above average seasons. Producers using the concept of a green date in setting dry season stocking rates are part of achieving the above aims of the program.

The concept of a green date, key dates, green season, green week or break of season and other terms have been around for many years to help determine when a break in the dry season may occur. Other key dates may be a sell date if it has not rained by a certain time in the dry season. A mid-dry season review date is also an essential part pasture budgeting process. The mid-dry season review date needs to take into consideration any events that could have changed feed quality since a feed budget was done at the beginning of the dry season. This may be events such as such as unseasonal winter rain that may either spoil stand-over dry feed or allow herbages to grow. In some areas of the north significant winter rain has the possibility of growing some pasture due to year-round warm temperatures. The mid-dry season review may identify the need to reduce stock numbers or maintain stock numbers if pastures are still adequate for the current stocking rate.

13.2 Objectives

Through a number of workshops such as NACP Forecasting for Decision Making, Climate Tools and Products, Climate Variability, and Grazing Risk Management workshops, grazing land managers have been trained in the use of the Climate App decision tool to determine a green date and how this information may be used in critical decisions on stocking rate.

13.3 Methodology

Dedicated climate workshops, climate update presentations, webinars, training modules and articles in print media have been used to make producers aware of the green date concept and how it can be used as a key management tool. The CliMate app has been used to calculate the green date as it has many long-term, rainfall recording station data available. The app is easy to use and there is no cost to download. The app also contains rainfall records as well as temperature indications for each centre. A range of other analyses make this a valuable decision analysis tool for any person managing in a variable climate. Climate records indicate that for the majority of locations in northern Australia that the end of March is the finish of the major growing season as rainfall totals, temperature and day length all decrease. A dry season pasture budget can be safely calculated from the 1st of April in most circumstances.

Knowing a green date can also be used for calculating the optimum time for calving or joining at a particular location. With the number of dry years many producers have experienced, some have opted to calve at a later date to ensure a better chance of feed for cows and calves. MLAs heifer management recommendations are: "*If using a 'green date', joining should commence one month* *after the 'green date' so that in most years, there will be a good body of feed available when breeders are lactating and cycling".*

A generalised estimate for the start of effective pasture growth is **50mm of rain over 3 days in 7 out of 10 years**. Most tropical pastures need a temperature of 20°C to grow, but moisture is usually the main limiting factor in the majority of northern grazing areas. The amount of rain needed to start pasture growth will vary, mainly based on soil type. Lighter, sandier soils require less rain to initiate pasture growth whereas heavier clay soils may require more rain. For example, the coastal area around Mackay, Queensland, has an estimated green date of 24 December, using the 50mm within 3 days thresholds. This area also has fairly heavy soils, so this is likely a good estimate of green date. By comparison, at Thargomindah there is not a green date of 50mm of rain over 3 days, so the rainfall amount has to be adjusted and the soils tend to contain less clay and more sand. In this case for Thargomindah there is a green date for 30mm of rain over 3 days on the 7th of March. Local producer knowledge about soils and pasture growth can be combined with the CliMate app to determine likely green date and end of season date.

13.4 Results

Over 45 NACP climate workshops have been held over northern Australian with a portion of workshop time spent explaining the concept of green date and how it can be used. The number of workshops and climate up-dates that have explained and given producers skills in using a green represents significant numbers of cattle being managed in the beef industry. In one workshop held in Queensland the participants managed/owned 86 000 hd of cattle.

13.5 Conclusion

13.5.1 Key findings

In northern Australia, the distinctive dry and wet season makes it possible to estimate how many days pasture feed is needed from the end of the growing season until good pasture growing rainfall is likely next summer. A pasture budget based on the probable length of the dry season enables a safe stocking rate to be calculated.

The reliable, long-term climatological start of the pasture growing season is called the green date. It is generally defined as the day after 1 September that a producer can expect to receive about 50mm of rain within 3 consecutive days in 7 out of 10 years. Climate Mates and NACP project staff have given producers across northern Australia the skills and knowledge to determine their green date. These green date parameters are refined depending on soil type and property location. Combining the green date with the likely end of the growing season date allows producers the ability to determine a dry season stocking rate. A safe stocking rate for available pasture has the potential to reduce the extent of supplementary feeding and reduces stress on pastures, stock, finances and the stock owner.

The use of a green date has the ability to improve the feed budgeting for the northern Australian beef industry. A safe stocking rate for available pasture has the potential to reduce the extent of supplementary feeding and reduces stress on pastures, stock, finances and the stock owner. The northern Beef industry using green dates will have greatly enhanced planning and response to climate variability and extremes.

16.3.2 Benefits to Industry

More accurate stocking rate decisions aligned to seasonal variability. Use of the CliMate App tool for a location gives an un-biased rigorous time period for feed budgets to be calculated. Subjective guessing of green dates is avoided.

13.6 Future research and recommendations

Defining green date for different land types using soil clay content

13.7 References

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14 Website

Laura Guillory, Jillian McCulloch, David Cobon
University of Southern Queensland, Toowoomba, Queensland, Australia

14.1 Background

The NACP website was launched in October 2019 and is divided into four main sections: Resources, Outreach, Forecasts and Drought Monitor. The website also hosts other documents relating to NACP such as reports & publications, videos and provides contact information for the Climate Mates.

The NACP website is available at https://nacp.org.au and is compatible with desktop computer, smartphone and tablet devices.

14.2 Objective

The NACP Website is designed to showcase the products, materials and activities delivered by the NACP program to the general public, producers, researchers and stakeholders. The website aims to be accessed via desktop computer, smartphone and tablet devices. It is designed to be practical, easy-to-navigate, engaging to the user, provide timely updates, be a repository of relevant climate information for all users and provide metrics on usage.

14.3 Methodology

14.3.1 Website Build

The NACP Website was built from the ground-up by the Web Developer to be specific to the intended audience and the objectives of the project. The Website and its updateable features are supported by the University of Southern Queensland's High Performance Computing Facility and ICT resources.

14.3.2 Website Maintenance

The NACP Website is maintained by the Web Developer with the use of the University of Southern Queensland's High Performance Computing facility and ICT resources. The website is updated monthly with maps and climate outlooks and website maintenance is completed weekly at a minimum and is reset if any technical difficulties are encountered.

14.3.3 Ease of Use and Relevance to Audience

The website achieves the objectives of being a showcase of the work of NACP by having an engaging scrollable home page, an easy-to-navigate menu at the top right of the screen, and clickable engaging relevant graphics. The website is being accessed via desktop computer, smartphone and tablet devices as outlined in the Results section below. The NACP website is engaging and practical by using easy-to-read, relevant headings, clear and practical use of images, use of a consistent colour scheme and minimal distracting features. The website achieves its objective of being an information repository by hosting archives, past research, maps and documents that can all be downloaded and used in any relevant application.

14.3.4 Measurability

Google Analytics is the tool employed to measure website usage and metrics. Climate Outlook metrics are obtained using MailJet software and can be selected for any temporal scale or website feature. These metrics are described below and presented at the NACP Conference.

14.4 Results

14.4.1 Website Features

Resources https://nacp.org.au/resources

The Resources page within the website hosts three sections – Videos, Climate Savvy for Grazing Management, Documents & Reports. 'Videos' hosts 10 videos aimed at producers to learn how NACP can assist with on-farm decision making, an introduction to the Climate Mates program and an in-depth discussion on La Nina and its affects on pasture management, soils and weeds. There is a 5-part series on the Green Date project including case studies. 'Climate Savvy for Grazing Management' divides northern Australia into a clickable map where users can select their area and download a PDF file of the grazing management guide for their area. The management guide is a high-quality document with information about climate drivers and grazing management tailored to the area selected by the user. 'Reports and Publications' hosts NACP scientific publications, reports, and publications from staff working on the NACP project from 2001 to 2021.

Outreach https://nacp.org.au/outreach

The Outreach page also hosts three sections – Climate Mates, Climate Training Course and Case Studies. Climate Mates is our unique and successful extension program that has seen expansion during the project. The website hosts contact details for the Climate Mates. A very successful part of the website, the Climate Training Course "Forecasting for Decision Making" is hosted within Outreach at https://nacp.org.au/outreach/training/launchpad. It is a free course designed to teach producers how to accurately read the Bureau of Meteorology's forecasts, understand climate drivers for Northern Australia and how to use forecasting tools and features a pre- and post- survey and workbook. Participants are offered workshops to complement their learning and are followed up by their local Climate Mate to assist with applications on their property. Case Studies hosts five downloadable case studies outlining how managing climate variability has assisted successful grazing management in our outreach areas.

Forecasts https://nacp.org.au/forecasts

Forecasts hosts the archive of Weekly Newsletters delivered by Professor Roger Stone from 2019 to 2021 and hosts the monthly Climate Outlook Review, which outlines climate conditions based on the current phase of the Southern Oscillation Index (SOI). Users can subscribe to the monthly Climate Outlook which is distributed at the start of the month.

Drought Monitor https://nacp.org.au/drought_monitor

The Drought Monitor is delivered online on the NACP website as an easy-to-interpret, colour-coded series of maps displaying various metrics related to drought. When this section of the website is visited, the CDI – Combined Drought Indicator which is a combination of rainfall, soil moisture, evapotranspiration and Normalized Difference Vegetation Index is displayed on the screen, with a clickable list to its right where users can select various drought-related indices at 1, 3, 6, 9-, 12-, 24- and 36-month timescales. These indices include the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Normalized Difference Vegetation Index (NDVI), Soil Moisture, Self-Calibrated Palmer Index (which quantifies the long-term drought conditions for a given location and time using dynamically calculated values) and the Palmer Z-Index (which measures short-term drought on a monthly scale). Users learn how to interpret the Drought Monitor, its origins and can download any map of their choice as a .jpg file.

14.4.2 Google Analytics Data

Metrics for NACP website – For the period October 2019 to February 2022 (NACP2)

The number of unique users of the NACP website for the described duration is 7737. The number of website sessions opened for NACP2 is 12269. For devices accessing the website, desktop computers account for 74.5% of devices, smartphone 22.419% and tablet devices 3.01%. The NACP website has surprising international reach. The top 10 countries accessing the website are listed in Table 1. Other website visitors are displayed on the map in Fig 1.

Domestically, Queensland has the highest number of website visitors as displayed in Table 2. Website components and their percentage visitation is outlined in Fig 2.

MailJet Analysis

The open rate of the weekly Climate and Weather email updates has improved from 26.5% to 32.5% over the course of the project and reaches 635 subscribers. The open rate of the monthly Climate Outlook Review email updates has improved from 31.5% to 39% over the course of the project and reaches 899 subscribers.

Figure 1. Geographical distribution of users of NACP website during NACP2. Darkest shades of blue indicate highest number of users (Google Analytics, 22 February 2022).

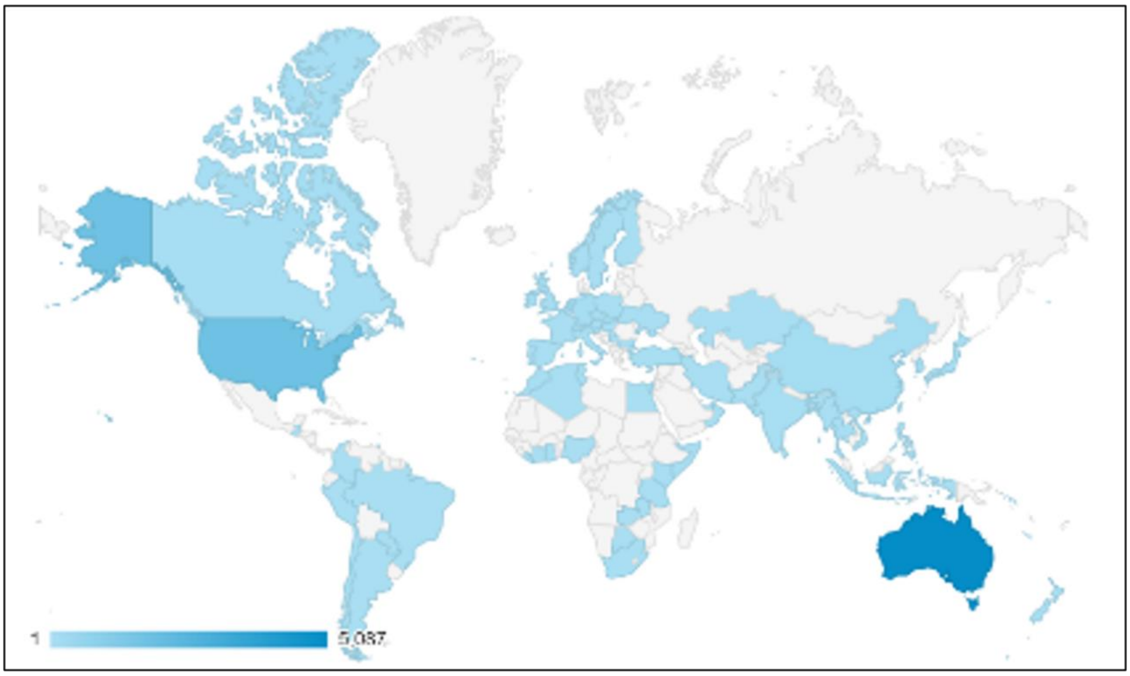


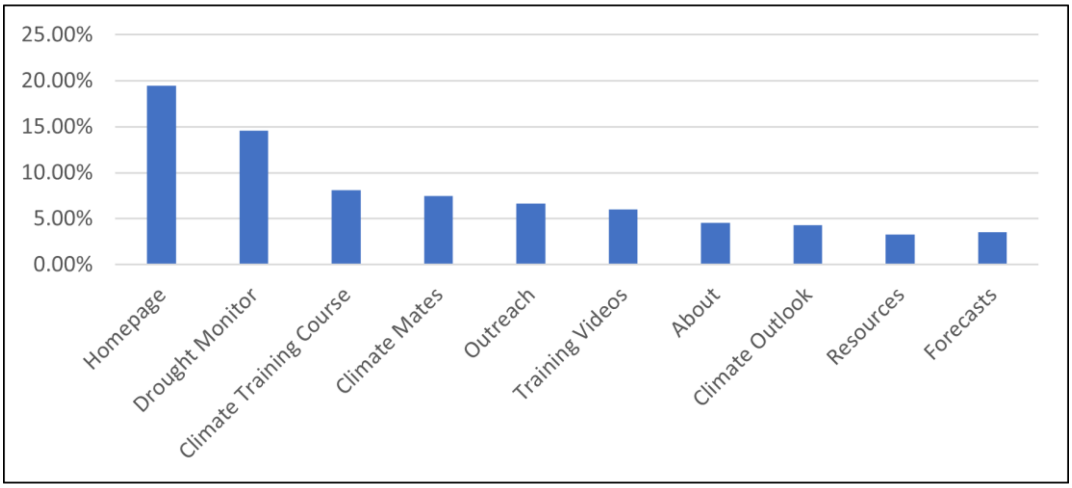
Table 2. Percentage of users by country for NACP website October 2019 – February 2022. (Google Analytics, 22 Feb 2022).

Country	% of Users
Australia	66.06%
United States of America	23.51%
China	1.94%
Germany	0.92%
United Kingdom	0.70%
Netherlands	0.70%
Canada	0.62%
South Korea	0.55%
Singapore	0.51%
Japan	0.30%

Table 3. Percentage of users by Australian State for NACP website October 2019 -February 2022 (Google Analytics, 22 February 2022).

State	% of Users
Queensland	56.84%
New South Wales	15.52%
Victoria	13.63%
Western Australia	4.77%
Australian Capital Territor	3.29%
South Australia	3.23%
Northern Territory	1.99%
Tasmania	0.72%

Figure 8. Percentage of visits per website component on NACP website October 2019 – February 2022 (Google Analytics, 22 February 2022).



14.5 Conclusion

14.5.1 Key Findings

The NACP website has been a successful addition to the NACP2 project and has fulfilled its objective to provide useful products, materials and activities generated as part of NACP2 to the general public, researchers, producers, stakeholders and industry.

16.3.2 Benefits to Industry

Through a publicly available, easy-to-access website, the NACP program has reached many users domestically and internationally. It hosts research done by NACP2, provides climate science training to producers and provides timely and useful data to producers and industry experts.

14.6 Future Research and Recommendations

Web Development is an integral part of the website's continued future in order to reach program participants and producers.

The website will allow for topic expansion and extended hosting of future NACP products and extension activities.

Include automation of products updates, interaction with products (Zoom into maps, hover and popups etc) and hosting of new products when they become operational (e.g. heat stress index).

15 Case studies

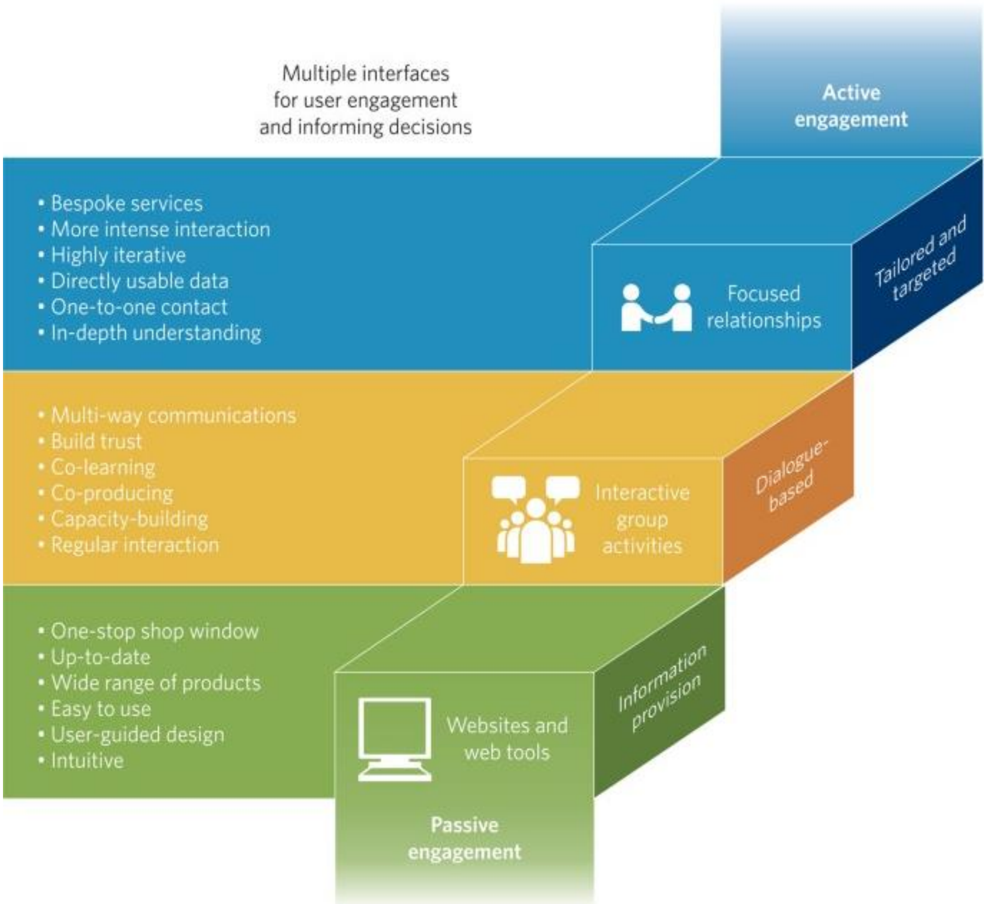
Kate Reardon Smith, Chelsea Jarvis, David Cobon, Climate Mates
University of Southern Queensland, Toowoomba, Queensland, Australia

15.1 Background

The NACP extension project is based on the theory of change outlined in Hewitt et al. (2017), which conceptualises the adaptation outcomes likely to result from a series of activities building from passive to active engagement (Figure 1). The authors of this paper propose that implementing the progressive steps of the 'staircase of engagement' will result in:

- a change in awareness resulting from passive engagement with information provided through presentations, newsletters, websites and tools (also referred to as Category A activities and outcomes);
- a change in Knowledge, Attitude, Skills and Aspirations (KASA) through dialogue-based activities such as active interaction in group workshops (Category B); and
- a change in practice which requires tailored and targeted discussions, often requiring active engagement through focused relationships and one-on-one face-to-face interaction (Category C).

Figure 1: The staircase of engagement: three broad categories of engagement between users and providers of climate services (Source: Hewitt et al., 2017)



While data are collected for all three steps in the extension program (see Section 16), the case studies reported here were specifically designed to document individual producers' experience of engaging with the NACP extension project and particularly the regional Climate Mates at the third (active engagement) stage and to identify outcomes in terms of confirmation of, or change in, current practices (e.g., using SCFs to inform decision-making), if reported.

15.2 Objectives

Develop engaging extension materials for NACP that provide examples of stakeholder engagement with the program and its impact on decision making in northern Australian livestock production enterprises aimed at better preparing for and managing climate variability. Specifically, it sought to capture (i) the ways in which producers are using climate information to better prepare for and manage climate variability to mitigate risk and sustain productivity; and (ii) practice change motivated by the improved understanding and access to climate services afforded by the NACP, particularly through the NACP Extension Project's team of Climate Mates.

15.3 Methodology

Semi-structured interviews were conducted with producers from different locations across the pastoral regions of northern Australia. Participants were all producers who had been involved with the NACP extension project; each was initially contacted by the regional Climate Mate with information about the intent of the Case study interview and the process. Once each had indicated their interest, follow up contact was made and additional participant information and consent forms were provided, in accordance with the USQ Human Research Ethics (HRE) approval for the project (H19REA224). All interviews but one were conducted by Kate Reardon-Smith at a mutually convenient time via Zoom; the remaining interview was conducted face-to-face by NACP associate, Kath Ryan, at the DPIRD office in Kununurra, WA. In all cases, the regional Climate Mate was invited to be a part of the conversation, although this was not always possible.

Interviews ran for approximately one hour and were recorded. Audios were then transcribed, and a copy of the transcription sent back to the participant and regional Climate Mate for verification and/or correction. Case study reports were developed from the interview transcripts, along with photographs contributed by the participants. Participants and Climate Mates had another chance to view the draft reports for any final clarification and to approve the final version before publication to the NACP website.

Data analytics from the NACP website have been used to track the interest in the case study reports by other producers, industry and research personnel.

15.4 Results

Five regional case studies were developed representing pastoral regions across the NACP project area, from Warwick in Southern Queensland to Kununurra in northern Western Australia (Figure 2). These represent a range of grazing enterprise types, from small breeding operations to large enterprises producing cattle for export market (Table 1). Case study participants reported a range of key climate-sensitive decisions for their operations (Table 2).

Figure 2: Case study locations

Table 4: Case study snapshots

Pastoral Region	Nearest town	Area (ha)	Breed	Herd size	Main market
WA The Kimberley	Kununurra	121,500	Brahman	5,800	Live export
NT Victoria River Downs/Sturt Plateau	Katherine	65,000	Brangus	1,100 breeders	Live export & (potentially) domestic
QLD Central North	Julia Creek	242,800	Brahman	16,000	Live export & domestic
QLD Southern Coastal	Gin Gin	1,200	Brahman x Senepol	~350 breeders	Domestic
QLD Eastern Darling Downs	Warwick	40	Black Angus	20 cows + calves	Domestic – weaner sales

Table 5: Key climate-sensitive decisions reported by regional case study participants

Pastoral Region	Key climate sensitive decisions
WA The Kimberley	• How hard to wean & when • Destocking – should we sell or move some to agistment?
NT Victoria River Downs/Barkly Tablelands	• All your budgeting • How much lick you'll need • When to employ staff and for how long • What kind of capital development projects you're going to tackle that year • How hard to wean & when; how many replacement heifers to keep • How hard to cull your breeders and how long do you have to carry them through until it's going to rain again "*The only way you do that is by having good information to make so that you can make pretty accurate decisions*."
QLD Central North	"*We're making decisions about next year's sale cattle at the end of the year – November-December-January – that's the critical period. If they're in good saleable condition and the market's good, we want to know if it's going to rain. If we don't think it's going to rain, we need to make a decision about whether to sell them now – or move them*."
QLD Southern Coastal	• When to wean • Do we feed • When to sell
QLD Eastern Darling Downs	• Feeding • Destocking – moving cattle to another property in a less drought affected area

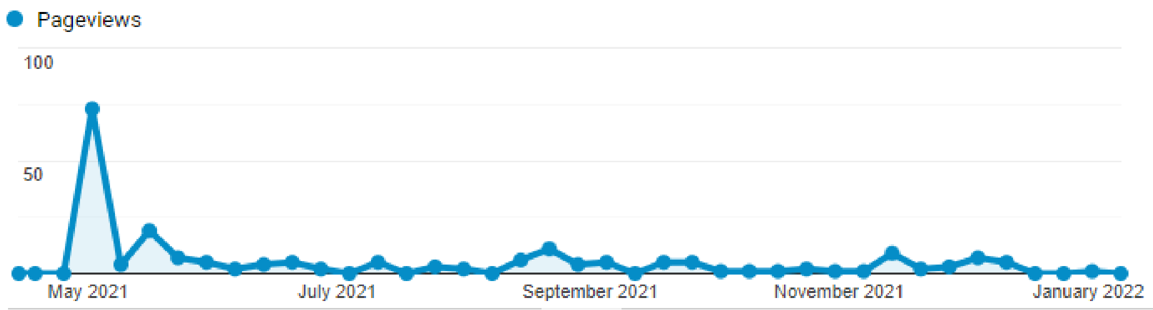
Key indications from the case study participants are that engagement with the NACP program and regional Climate Mates (Table 3), and specifically the facilitated access to and improved understanding of climate forecast information afforded by the NACP Extension Project, has provided a valued and valuable support platform for improved decision-making. Having access to and the ability to interpret forecasts to gain an early indication of seasonal conditions was seen as critical to their ability to plan ahead and prepare; this includes making stocking/destocking decisions to ensure both animal welfare and pasture/land condition. Feedback from the case study participants also confirm the need for regional targeting of climate information to particular key climate-sensitive decisions with sufficient lead-time for decision-making.

Table 6: NACP engagement & impact for case study participants

Participant's region	Category A	Category B	Category C	Practice change
WA The Kimberley	BoM website – weather forecasts, synoptic charts, radar	…	One-on-one face-to-face session exploring and discussing seasonal forecast information	Planning stock movements between properties based on pasture condition and forecast information
NT Victoria River Downs/Sturt Plateau	…	Presentations at Northern Beef Research Council and NACP climate workshop	One-on-one remote session on the BoM developmental tools	Using seasonal forecasts and information to help with budgeting, estimating lick requirements and operational planning
QLD Central North	…	NACP workshop participant	…	Since the workshop, using the online tools & the BoM website, especially for wet season management decisions about cattle numbers and movements between company and/or agistment properties.
QLD Southern Coastal	NACP monthly seasonal outlooks	…	'Really useful' one-on-one interactions with Peter	Using the forecasts & information from seasonal outlooks, along with pasture condition assessments, in decision-making about stocking rates, cattle sales and enterprise mix.
QLD Eastern Darling Downs	---	NACP workshop participant	One-on-one face-to-face discussions re regional climate forecasts and property-level forage reports	Destocking & cattle movement decisions between two properties (Warwick, Glen Innes) based on seasonal climate and pasture growth forecasts

Google analytics on the numbers of online views of the case study reports, dated from when they were first posted to the NACP website in April 2021, indicate that there has been a total of 201 page views (Figure 3), but that, following an initial spike in interest, these then tailed off and have since remained at a relatively low level, with occasional peaks. By comparison, one of the case study participants (and the regional Climate Mate) also agreed to the filming of a short video, which has received 116 views since it was posted in November 2020. See: What is a Climate Mate?

Figure 3 Google analytics results (April 2021 – January 2022)



15.5 Conclusion

15.5.1 Key findings

Five regional case studies were developed to provide engaging examples of the ways in which a selection of producers in different northern Australian pastoral regions are using climate information to better prepare for and manage climate variability to mitigate risk and sustain productivity. These aimed to capture practice change associated with improved understanding and access to climate services afforded by the NACP, particularly through the NACP Extension Project's team of Climate Mates. The case studies represent pastoral regions across the NACP project area (Warwick, Southern Queensland; Gin Gin, Central Qld; Julia Creek, Northwest Qld; Barkley Tablelands, Northern Territory; Kununurra, northern Western Australia).

Key indications from the case studies are that engagement with the NACP program and regional Climate Mates, and specifically facilitated access to and improved understanding of climate forecast information, has provided participants with a valued and valuable support platform for improved decision-making. Case study participants report that having access to and the ability to interpret forecasts to gain an early indication of seasonal conditions is critical to their ability to plan ahead and prepare. This includes making stocking/destocking decisions to ensure both animal welfare and pasture/land condition.

16.3.2 Benefits to industry

These case studies provide insight into how individual producers have engaged with and responded to the NACP Extension project in terms of enhanced knowledge and practice change. As a form of story-telling, they provide others with a chance to engage with easily-digested information that is contextualised and relatable for their own location and enterprise. They also provide a level of evidence (though biased) of the success of the program and its impact on individual operations.

15.6 Future research & recommendations

As a communication tool, case study reports are static and, once viewed, unlikely to be accessed multiple times. Future projects might look to use these in combination with other more engaging formats that add value (e.g., follow-up videos and/or updates on the case studies and decisions as seasonal conditions evolve).

15.7 References

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

16 NACP extension and adoption

Chelsea Jarvis, Sally Foreman, Climate Mates
University of Southern Queensland, Toowoomba, Queensland, Australia

16.1 Background

16.3.2 NACP Extension

The extension component of NACP forms the essential link between research and on-ground adoption of tools and improved business resilience. The goal of the extension project is the development and delivery of programs to help the northern Australian grazing industry manage drought and climate risk by improving regional climate forecasting tools and supporting practical and locally based seasonal forecast and climate risk management strategies.

A critical component of the extension project is the 'Climate Mates'—individuals selected for their knowledge of the industry and their capacity to network and communicate with producers in key red meat regions to improve the use of weather and climate forecasts through training and engaging with graziers, advisors and supporting the broader extension team across northern Australia. 'Climate Mates' are supported by an agricultural climatological expert to understand contemporaneous climate forecasting for use within their extension programs. This expert also aids in the delivery of workshops and training to industry. The Climate Mates also take feedback received from producers and communicate it to BOM and UKMO project partners to aid in the focus of research and development tools.

Highly successful climate and product workshops, which have been run across beef, sheep and cropping industries for nearly three decades, were used as a starting point for NACP extension. These workshops were supported by the Climate Mates, the project expert, and BOM partners, and run, when possible, with existing extension networks and groups. They update the industry on current weather and climate knowledge, and also feed industry needs for forecasting products and climate tools back to the research teams within the project.

This approach created an embedded feedback loop, connecting red meat businesses with project scientists from USQ, DES, BoM and the UKMO. It hastened adoption through direct contact and by providing relevant industry information to answer direct needs for on-ground management and embedded client focus in the research and product development. The approach supported the grazing industry in northern Australia to manage risks associated with the impacts of climate variability and make the most of grazing management and business opportunities season by season.

16.1.2 Industry issues to address

The issues that the NACP extension sought to address were identified in NACP1 where 250 producers and 50 advisers/ community members were surveyed about the climate needs of northern Australia:

- Low producer skill in finding, interpreting, and applying seasonal forecasts to property management decisions, including decisions around drought
- Low producer uptake and use of seasonal forecasts
- Lack of use of forecasts and climate products in drought risk management, sustainability, and productivity

- Low understanding of when to use forecasts and their limitations

The proposed outcomes of the extension component of NACP2 included:

- **Improved knowledge** among advisers and primary producers in seasonal forecasting, climate and drought by providing workshops, seminars, webinars, media content, etc. that provide information on how to correctly use and interpret forecasts and climate information
- **Improved use of seasonal forecast products** with more graziers using seasonal forecasting in operational and strategic decision-making leading to increased profits by working with producers one-on-one to understand their business and where forecasts can fit into their plan
- **Improved capacity** of grazing business to be resilient, sustainable, productive and profitable by using improved climate knowledge in decision making
- **Improve drought risk management** by increasing producer literacy of climate information and forecasts so as to reduce impacts of drought/failed wets for northern Australia
- **Improved understanding** of when to use seasonal forecasts and the limitations of forecasts by region and season, as communicated by NACP extension at workshops, one-on-ones, etc.
- **Monitor changes in KASA** and demonstrate impact and return on investment, which can be used to guide future investments and evolutions in the NACP extension program

The NACP extension program is unique from other programs for two main reasons: One, the Climate Mate model; and two, the vertical integration of extension with R&D. The Climate Mates, regionally located producers and those in related fields, were hired for their connections to industry and their region rather than for climate skills. This ensured that NACP extension was able to immediately connect and communicate with producers, as the producers already trusted and had a relationship with the Climate Mate. This 'local champion' approach has been used elsewhere, but not to the extent as it has with NACP. The Climate Mates provide an ongoing legacy in their region. The NACP structure of linking extension with R&D and providing a two-way flow of information between R&D and producers with the Climate Mates as intermediaries was unique to NACP and invaluable in ensuring that producer R&D needs were met and producers felt like they were being 'heard' by scientists.

16.3 Objectives

NACP extension objectives included:

- More resilient grazing businesses using climate knowledge in a whole-of-business management approach to decision making
- Improved capacity of grazing business to be sustainable, productive, and profitable
- More grazing businesses planning for variable and extreme climate events to manage risks and take advantage of opportunities
- Improvement in business key performance indicators related to improvements in management of climate variability
- Delivery of legacy products, resources and systems that will continue beyond the life of the project.

16.3 Methodology

16.3.2 Key Primary Indicators KPIs

The NACP extension team were tasked with reaching Category A, B, and C goals and used a number of methods to reach these goals. Targets were expanded when the number of Climate Mates was increased from eight to 16 and are shown in Table 1.

Table 1. NACP Extension targets and accomplishments for Category A, B, and C KPIs

	Target, Producers	Target, Others	Current, Producers	Current Others	% Total Producers	% Total Others
Category A	5500	150	16,271	35,295	exceeded	exceeded
Category B	420	65	1,509	888	exceeded	exceeded
Category C	150	35	161 MLA / 231 DCAP	49 MLA/ 79 DCAP	91%/132%	111%/197%

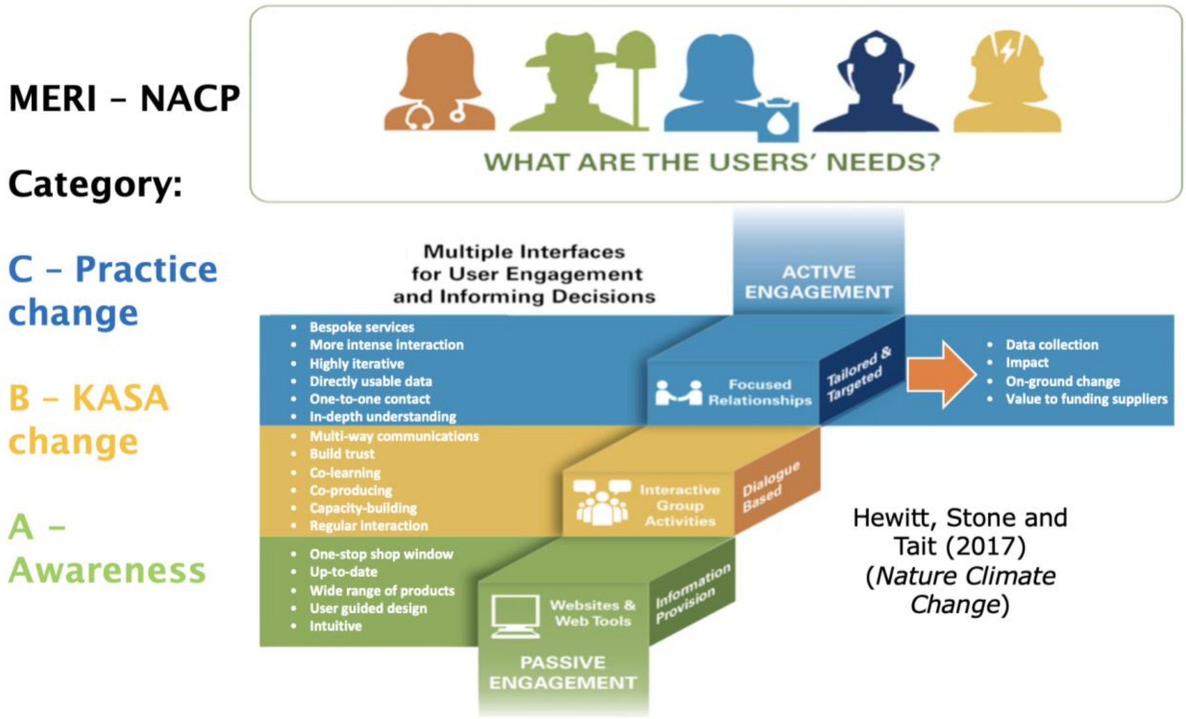
Categories were divided between producers and other related supply chain and extension specialists. The purpose of Category A targets was to raise awareness of the NACP and examples include presenting information on NACP at field days, calling producers directly, and emailing and connecting with other extension programs. Category B addressed improving knowledge, aspirations, skills, and attitudes (KASA) regarding NACP's goal of improving the use of weather and climate forecasts by producers. Examples of Category B include providing Climate Workshops, one-on-one meetings to install climate apps and explain use, and reaching out to other extension specialists to provide them with climate information to include in their toolbox. Category C targets addressed practice change. Practice change occurs when a producer decides to incorporate weather or climate information into their business plan and when other extension officers include climate information into their workshops, etc.

16.3.2 Monitoring, Evaluation, Reporting, and Improvement (MERI) Plan

The NACP MERI plan guided the extension team to develop, deliver, record, and review programs to help the northern Australian grazing industry manage drought and climate risk by improving regional climate forecasting tools and supporting practical and locally based seasonal forecast and climate risk management strategies. The structure of the MERI plan paralleled that of the NACP Milestone requirements to ensure NACP extension was meeting funder's requirements. The MERI plan also identified possible barriers and ways to overcome those barriers.

The NACP MERI plan reflected Hewett, et al (2017) 'stairway to engagement' (Figure 1). In this structure, a producer becomes aware of NACP (for example by social media), then engages with NACP, for example at a workshop, where the producer learns a new skill. After learning a new skill, NACP extension follow up with the producer to provide one-on-one advice that allows the producer to determine how to use the NACP information for their own property management plan. Ideally, this advice leads the producer to make a decision that is partially informed by NACP information.

Figure 1: The staircase of engagement: three broad categories of engagement between users and providers of climate services (Adapted from source: Hewitt et al., 2017)



16.3.3 Communications (COMMS) Plan

The NACP Communications plan targeted northern Australian red meat producers (cattle and sheep predominately) in Queensland, the Northern Territory, and Western Australia, as well as those in the associated Industry value-chain.

The communications plan included the following targets:

- To improve the knowledge and skills of producers across the grazing industries to support proactive management of climate variability which minimises exposure to environmental, profitability, and productivity losses due to drought or drier than normal wet season, and maximises opportunities presented in above average seasons
- Build capacity of producers to better manage climate risk through using knowledge of historical climate and climate forecasts in decision making
- Encourage producer engagement and practice change
- Communicate benefits and value of climate forecasts, including seasonal, multi-week, and multi-year
- Improve understanding and uptake of forecasts for use in strategic decision making
- Improve climate literacy and raise awareness of regionally relevant decision support tools.

Communication methods in the original COMMS plan to allow NACP to meet communications targets included e-newsletters (eg Future Beef), traditional news sources (e.g. Queensland Country Life), industry journals, scientific journals, presentations by the NACP extension team (eg workshops, field days), social media, and a website.

16.3.4 Videos

Short, informational videos developed by NACP2 were not an original part of the COMMS plan. However, due to COVID, the making and use of videos became very important to allow NACP to continue to connect with producers. Short videos proved to be a useful communications tool that will be further utilised in NACP3.

16.3.5 Social Media

While social media was mentioned in the original NACP COMMS plan, there was not a lot of initial effort put into developing this communications strategy. After meeting with producers, it became clear that many of them spend quite a lot of time on social media, especially Facebook. Because of this, NACP2 encouraged the Climate Mates to develop their own regional Facebook NACP page. This turned out to be a good strategy (as discussed below in 'Results') and will be further pursued as part of NACP3.

16.3.6 Regional Climate Guides

At the first annual NACP meeting in 2019, it became clear that the Climate Mates would benefit from having more information on the climate drivers specific for their region and possible management decisions related to those drivers. Short informational booklets, called 'Regional Climate Guides' were developed by senior NACP extension along with guidance from NACP/BOM.

16.3.7 Reporting

Accurate and robust reporting and recording of NACP2 extension activities, including Category A, B, and C goals, were imperative to show progress against KPIs. Two main methods were used for reporting: A spreadsheet to track Climate Mate activities, and narratives that provided more in-depth information on practice change and other important activities. Impact analyses were conducted near the end of NACP2, as requested by MLA.

16.3.7.1 Spreadsheet

A spreadsheet was developed using Microsoft Excel that allowed for the tracking of Category A, B, and C goals. Each Climate Mate was provided a copy of this spreadsheet. The Climate Mates then filled in their own activities against each Category goal and sent an updated spreadsheet back to the head of the extension team. The head of extension then merged all of the spreadsheets into one 'Master' spreadsheet and used Excel to calculate the number of activities in each Category as well as how many producers and 'others' attended each event. The benefits to this system were that it was easy to develop and all of the Climate Mates already knew how to use Excel. The drawbacks were that once the program was expanded from 8 to 16 Climate Mates, collating all of the data took a considerable amount of time.

16.3.7.2 Narratives

Narratives are short documents that summarise an interaction with a producer or producers, including a reflection on the interaction that allows for future learnings and application. Narratives were used especially to provide in-depth documentation of Practice Change.

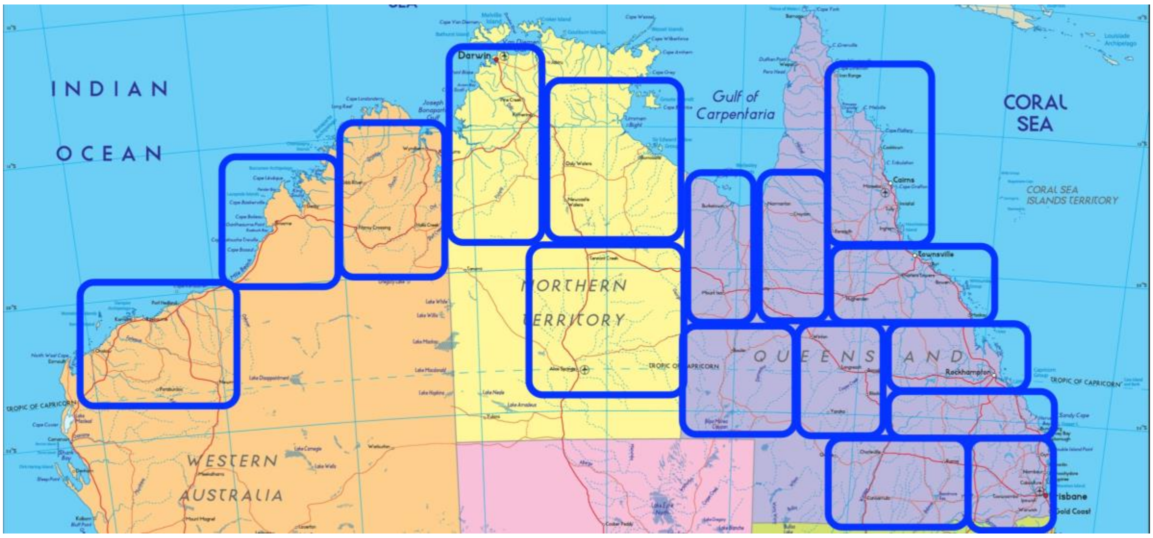
16.3.8 Impact Analysis

In 2021, the NACP was asked by MLA to determine any economic, environmental, or social benefits of the NACP. Data, such as financial data, were collected from producers who used information from NACP, at least in part, to make or support an on-property decision. Nine such analyses were conducted and provided useful insight into the benefit of the NACP. NACP3 aspires to include more impact analyses. A drawback to conducting these impact analyses was that MLA was unable to provide any guidelines or strategies to collect this data.

16.3.9 Climate Mates

The NACP's extension officers, called 'Climate Mates', were critical to the success of the NACP, including facilitating the two-way flow of information between NACP R&D and producers. The NACP program started with 8 Climate Mates working one day per week (0.2FTE) and was expanded in early 2020 to be 16 Climate Mates at one day per week. The Climate Mates are located across northern Australia (Figure 2). Approximately half of the Climate Mates are producers and live on-property and the other half work for a natural resource management group. Each situation has its own benefits, as will be discussed in the Results section.

Figure 2: Climate Mate locations



16.3.10 Hiring

NACP extension originally consisted of a full-time climatologist with a background in agriculture, a part-time climate/agricultural expert based at Queensland DAF, and eight Climate Mates. In 2020, the team was expanded to another part-time support role and additional Climate Mates.

The 'Climate Mates' were hired based on their knowledge of the red meat industry in their region as well as their local regional networks, rather than based on their climate knowledge. This hiring strategy avoided the lag of building trust with local producers that results from hiring someone with specific expertise (e.g. climate) but from outside the region. This strategy was overall successful, as the Climate Mates were able to immediately connect with producers in a meaningful way. The main drawback was that there were a limited number of applicants in remote regions.

16.3.11 Training

Training in weather, climate, and extension methodologies was provided to the Climate Mates shortly after hiring. There were two rounds of training, one in August 2018 for the initial eight Climate Mates hired, and then a second round in May 2020 when the Climate Mate program was doubled in size to 16 Climate Mates. The first round was held in Toowoomba and was attended by all Climate Mates and NACP-associated BOM staff. This training consisted of a 5-day intensive climate program. The second round was held virtually, due to COVID. Approximately 16 video modules were created, which covered all aspects of climate and extension. Climate Mates watched approximately 4 videos per week and then two Zoom sessions were held per week for four weeks with all Climate Mates as well as selected NACP-BOM staff attending to discuss the videos and answer any questions.

Climate Mates reported that the first training session was too intensive and overwhelming. There was too much focus on climate information and not enough on how to actually apply this information. This feedback was taken on board when designing the second training, which had much more positive feedback. The Climate Mates in the second round of training liked having delivery of the information spread-out over 4 weeks so that they had time to process it. Also, they liked having videos they could revisit.

Climate Mates were provided with annual training at the NACP Annual Meeting. Throughout the year, Zoom meetings were also held to ‘up-skill’ Climate Mates. These Zoom sessions regularly included NACP/BOM employees.

16.3.12 Activities

NACP extension activities targeted red meat producers, associated supply chains, and associated NRM and government groups across Queensland, Northern Territory, and northern Western Australia. Extension activities generally fell into one of four categories: NACP-organised events; events organised by another group, including conferences; one-on-one or small groups; remote/distant events and interactions. Activities in all four categories were needed for a robust extension program. Events organised by other groups were good to raise awareness of NACP (Category A) with minimal time/costs for NACP staff. Events organised by NACP allowed for knowledge and skills sharing (Category B). One on one events were critical to achieving Practice Change (Category C). Online/distance events were needed to continue to connect with producers during the COVID pandemic/epidemic.

NACP extension developed three ‘signature’ workshops: Forecasting for Decision Making; Climate and Weather Tools Online; and Climate Integrated On-property Management. Additionally, an online climate course was created and can be found on the NACP website.

16.3.13 Benchmark Survey

NACP extension undertook a benchmark survey in 2019 and 2021 to collect Climate Mate feedback on their experiences in the role. The survey asked questions about Climate Mate training, support provided, things that worked well, and areas that needed improvement. The survey results helped guide the evolution of the NACP extension program. These surveys proved to be a valuable way to quickly and easily collect Climate Mate feedback.

16.4 Results

16.4.1 KPIs

NACP extension KPIs focused on reaching a certain number of producers and industry-associated 'others' to raise awareness (Category A), increase KASA (Category B), and achieve practice change (Category C). These numbers are shown in Table 1. The NACP extension was successful in achieving and exceeding all of the Category A, B, and C KPIs.

For Category C, two of NACP's funding bodies had different definitions of what constituted 'Practice Change'. For MLA, practice change was linked to a specific decision (eg a producer decided to sell cattle early due to a dry forecast). For DCAP, it was enough that a producer changed or developed a new a habit (e.g. the producer now *regularly* looks at climate forecasts because of NACP whereas before they did not). DCAP total numbers include the instance of practice change that met the MLA definition.

16.4.2 MERI Plan

The NACP2 MERI plan was developed and completed in time to reach the deadline put forth in Milestone 2. The MERI plan was then updated with accomplishments for every mid-year and annual MLA report. The final, updated MERI plan, can be found in Appendix A.

While the NACP2 MERI plan provided guidance and a framework to meet NACP2 goals, the MERI plan will be overhauled for NACP3. This is due to needing a MERI plan that reflects new Milestones, KPIs, and a new reporting system.

16.4.3 COMMS Plan & COMMS Activities

The NACP COMMs plan provided guidance as to ways NACP extension could meet their KPIs. Actual strategies used were informed by this plan and evolved with the project. More detailed information for each category of communications can be found below. For the NACP COMMS plan, please see Appendix B.

Traditional Communication Methods

Traditional methods of communication, such as newspapers, e-newsletters, radio, and TV, have been widely used to promote the NACP. Climate Mates contribute to e-newsletters while head of NACP extension has provided radio, TV, and newspaper interviews. Gains in awareness (Category A) of NACP via traditional methods (newspaper, TV, radio) was widespread, though frequently it was difficult to know who was actually exposed to the communication (e.g. producers specifically or the general public), as the only number usually provided to NACP was the 'reach' of a communication, i.e. the total number of people that received that particular newspaper or listened to that particular radio station. Hypothetically, if these media reaches were counted at 1% of the total, they would add an additional 4,721,204 individuals to the Category A total (Table 2).

Table 2. Summary of traditional media communication activities undertaken by the NACP extension team from 2018 to January 2022.

Activity Type	Number of Activities	Examples	Reach
Articles, including newspapers and e-newsletters	42	The Conversation, Rural Weekly, Courier Mail, Local newspapers (eg Agnes Coastal Rag)	673,527
Radio	33	BBC, ABC, Triple M, Zinc, River949	446,000
TV	13	Landline/ABC, 7 News, WIN	158,000
Magazine	1	Qantas Link (on all Qantas flights)	32,500
Podcast	1	DCAP Podcast	200

Informational Videos

NACP developed a number of short, promotional and/or informational videos around climate and producer decisions. The impetus for these videos was the original COVID lockdown, as the videos allowed us to continue to provide new content to producers. These videos turned out to be very popular and so more were developed. NACP was also approached by Capricornia Catchments NRM to make a series of videos about the Green Date. Capricornia Catchments NRM provided the drone (including a pilot and all footage) as well as cattle producer's property at which to film. Making these videos met the needs of both Capricornia Catchment as well as NACP and provided NACP with approximately $2,000 of in-kind benefits.

During the project NACP extension had the opportunity to work with USQ media staff to produce a short informational video explaining the role of the Climate Mates. The video was very well received and lead to NACP extension further incorporating short informational videos into extension activities. A more extensive NACP extension video that included both producers and the supply chain was shot in the Northern Territory, to engage further with northern Australia producers.

Short informational videos provide value in a number of ways. They explain ideas and concepts in simple and relevant ways and are much more enticing then written documents. Producers, those in the red meat supply chain, and those who regularly work with producers were included in these videos to provide the most relevant and relatable content. This approach added credibility to NACP extension by showcasing feedback from producers for producers in our target area. NACP videos are used for social media, at conferences, at workshops and at field days.

These videos also provide an authentic snapshot for NACP funding partners to show the impact the project is having on ground, in a way that is easily understood and appreciated.

The videos are a legacy product that are currently hosted on YouTube and the NACP website (nacp.org.au).

Social Media

The use of social media has evolved over the project (Table 3). Originally, social media was only used in conjunction with DCAP/QLD government Facebook page, with NACP providing content for their posts. NACP extension identified social media, in particular Facebook, as an opportunity for the Climate Mates to have more local interaction with producers through having their own Facebook pages which were regionally specific.

Climate Mates Facebook Pages:

NACP extension currently has six Facebook pages active over the project area. All pages are administered both centrally and by the local Climate Mates. Using Facebook allowed much more regionally specific information to be shared and advertising of local events and workshops to be coordinated. When appropriate, Climate Mates created a combined Facebook page (ie two or three Climate Mates posting to the same regional page), which provided for efficiencies in content creation. When COVID restricted movement, especially in isolated areas, social media was a key tool to boost Climate Mate engagement with producers.

NACP extension has found that Facebook pages are an excellent platform to release regionally relevant forecast information and engage with producers in a local area. NACP Facebook pages have consistently grown in follower numbers, with there now being 2,227 followers across our local climate pages in the project area.

Facebook advertising

NACP extension used Facebook advertising for local workshops across the project area. The average cost of an ad was $66. Effectiveness was measured through engagement with the post, and feedback from the Climate Mates as to how many attendees mentioned seeing advertising on Facebook. The ads reached 71,724 people over the project area, and there was active engagement of 7,894 people in response to NACP posts boosted with paid advertising. Climate Mates reported that between 25-50% of attendees at workshops saw the workshop advertised on social media. As such NACP extension will continue to use Facebook advertising as a cost-effective tool for advertising events over the project area.

One drawback of Facebook use is some Climate Mates are not as comfortable using social media as others, and therefore do not engage with it as much. Therefore, benefits of Facebook use weren't consistent across the whole project area. Better results were observed in the areas where the Climate Mates posted and interacted regularly. There is more scope to increase use of social media in NACP 3 to drive qualified leads to the project as well as to dedicate more training to the Climate Mates on the functions of social media.

Table 3. Reflections on social media use during NACP2

Action Item	Social Media Use
First Try	Social media was only done through the DCAP/QLD gov agriculture Facebook page. This was advised due to time associated with producing content
First Try Reflection	NACP provided some information for the QDAF Facebook page but had little control over timing of posts or comments etc.
Second Try	When the number of Climate Mates doubled, we decided to group them together and launch regional climate Facebook pages. This was to publish regional outlooks, relevant climate information and to advertise workshops/events

Second Try Reflection	This was successful in gaining traction in the Climate Mate regions and an estimated 25 - 50% of attendees at workshops saw an ad of Facebook. Over 2,000 local people follow the pages. Content included videos, forecasts, weather warnings and upcoming events.
Future Advice	Social media will be used more extensively to drive qualified leads to the Climate Mates, it will be used for advertising and awareness over the future project

Online Training Program

The NACP Online Training Program (currently found at nacp.org.au) evolved from the Climate Mate training video modules. The video modules were simplified and streamlined in order to provide climate information in short sharp videos for producers. A benefit to this online program for producer was that it allowed us to collect information (email addresses) on anyone who signed up. This information was then passed on to the Climate Mates who followed up to determine if the person would be interested in attending a workshop or other event. To date, 286 people have completed the online course.

NACP3 will see an overhaul of this course to provide more targeted information as well as short quizzes to demonstrate increases in knowledge. The online course is a valuable resource to upskill producers, one we can use for lead generation in NACP 3, and is also a legacy product.

Regional Climate Guides

Eight regional climate guides covering major regions within NACP's operational area were created in 2020 in response to Climate Mate feedback. Colour booklets were printed and sent to Climate Mates to be used for their own reference as well as in interactions with producers at workshops and other events. The Regional Guides were popular amongst producers, with producers frequently taking a copy of the booklet when offered at events.

These booklets were popular because they were:

- Addressed specific regions (which is very important to producers)
- Easy to read and understand
- Linked management decisions with climate drivers
- Colourful and approachable.

Monthly Climate Outlook

Roger Stone and Chelsea Jarvis, with assistance from Lynda Brunton, produced monthly climate outlooks that covered all of northern Australia. Content included a summary of current conditions as well as what was expected in the coming months, based on a variety of models, including a pasture growth model. The Climate Outlook was distributed via email and also available on the NACP website.

The Climate Mates produced supplementary information that was sent in addition to the monthly Climate Outlooks that provided more detailed information on a regional basis. Many of these supplementary outlooks were well received (based on feedback from producers) and provided producer-relevant information. As part of NACP3 reporting, NACP will be recording how many people opened and read both the Monthly Outlook as well as any supplementary information to determine exactly how many producers were accessing this information regularly.

16.4.4 Reporting

Spreadsheet

The NACP reporting spreadsheet, filled in by each Climate Mate and sent to head of NACP extension each quarter, was able to adequately capture relevant details regarding Milestones and KPIs. However, it was not the most efficient method. The proposal for NACP3 includes an updated reporting system that will collect more information, and be easier and timelier to use. A reflection of the current spreadsheet system can be found in Table 4.

Table 4. Reflection of the NACP spreadsheet reporting system.

Action Item	Reporting
First Try	Spreadsheet that captured Category A, B, and C targets and Climate Mates entered their information into the YourData DCAP system; Narratives in the YourData system
First Try Reflection	Having the Climate Mates enter their own data into YourData did not work as the system was not intuitive. Head of NACP extension received a spreadsheet once per quarter from each Climate Mate and then copied and pasted the information into a 'Master' spreadsheet. This system worked due to their only being 8 Climate Mates and allowed the head of extension to review the data before entering it into the YourData system.
Second Try	Continued with spreadsheet, but CM no longer entered their own data into YourData. This was due to quality control issues (items being entered incorrectly) as well as some CM being uncomfortable using the technology.
Second Try Reflection	With 16 CM, the spreadsheet system became cumbersome and made organising final reporting numbers time consuming - however - at that stage in the program, it did not make sense to implement a new recording system. Having one person review and enter data into YourData worked well.
Future Advice	A more strategic and comprehensive data collection system is being worked on for NACP 3. This would add an intuitive CRM system which would prompt the capture of more data at the source, feeding it into a customer (producer) database. This would be collaborated for each CM automatically. Reporting would be more easily generated. This system is currently being designed and we hope to bring it to the start of NACP 3.

Narratives

From August 2018 to January 2022, NACP extension produced 48 narratives. The purpose of the narrative was to reflect on an event of particular importance, such as how a producer achieved practice change. The benefits of narratives were that they were generally quick to produce and also provided information that other Climate Mates could review and learn from. The main drawback of the narrative was that the structure in the DCAP database did not necessarily encourage Climate Mates to ask the questions that would lead to more detailed economic/environmental/social outcomes. This has been rectified in the plan for NACP3, with the new reporting system able to more effectively capture this data. A list of narratives can be found in Appendix C.

Impact Assessment

NACP extension reviewed achieved practice change to date and followed up with 9 producers to gather more information related to the economic, environmental, and social benefits gained due to interactions with NACP. This information was turned into a series of case studies (Appendix D). A **benefit of between $15.73 and $27.89 per head per year** was found based on the following assumptions: There are 15M head of cattle in northern Australia; NACP will reach producers responsible for approximately 25% of the total herd (3.75M head); and 20% of the practice change can be attributed to information and consultation provided by NACP. This is equivalent to an return on investment of the 4-year term of NACP of between 6:1 and 10:1.

Reporting for NACP3 has included the collection of data required to conduct impact assessments. The NACP2 impact assessments can be found in Appendix D.

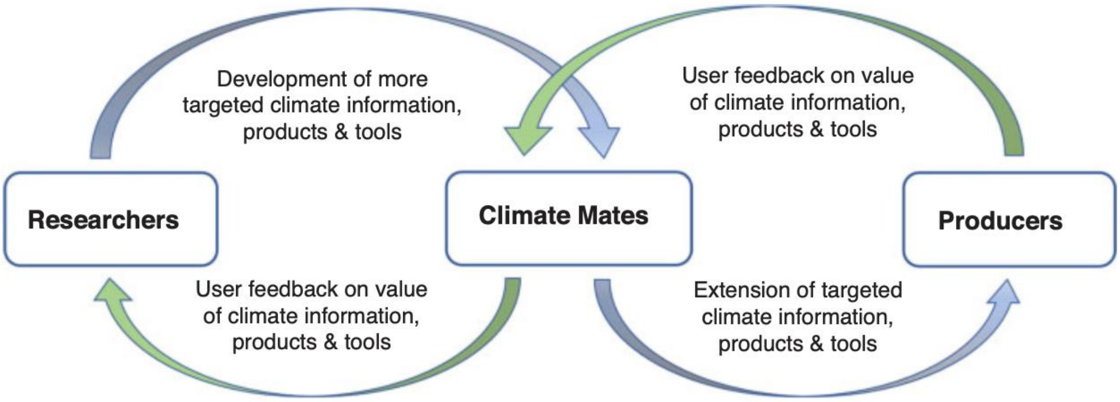
16.4.5 Climate Mates

The Climate Mate model for extension, which focused on using regionally located individuals with deep connections to the red meat industry, was an efficient and successful system. The initial success of the 8 original Climate Mates (2018/2019) led to the program to be doubled in 2019. The main benefit of hiring someone from within the region is that it eliminates the time normally required to build local knowledge and networks. The main drawback encountered was the time required to bring the Climate Mates up to speed regarding weather and climate information and forecasts. However, the benefit of realising the time required for the Climate Mates to learn this information was that it made clear how to communicate this information to producers in an approachable and understandable way.

One major strength of the Climate Mate program is the connection to NACP R&D (Figure 3). The flow of information from researchers to producers via the Climate Mates allowed the NACP R&D to target producer needs. Having this connection also allowed the Climate Mates to directly contact a NACP/BOM employee when they had specific and/or challenging weather and climate questions. NACP BOM employees attended and presented at NACP workshops and roadshows, which had the following benefits:

- Producers were able to 'put a face' on the BOM, which increased trust – trust was identified in NACP1 as a major barrier to producer uptake of forecast products
- NACP/BOM employees directly interacted with producers and understood their needs and then tailored R&D to these needs
- Climate Mates gained knowledge by interacting with the BOM during the workshops/roadshows
- The relationship between the Climate Mates and the NACP/BOM strengthened.

Figure 3: A schematic showing the relationship and integration of researchers (and developers), Climate Mates and producers (Cobon et al 2021)



Hiring

In 2020, the NACP extension team hired another part-time employee to assist with the management of the additional number of Climate Mates. This new team member had a background in agriculture as well as marketing. Hiring a staff member with a marketing background proved key in improving the NACP extension program and bringing in new ideas as to how to be more productive and consistent.

NACP2 had few issues arise around hiring. The main issue was the small pool of applications from remote regions, which sometimes necessitated advertising for a role for an extended period of time. Table 5 reviews further benefits and drawbacks of hiring for NACP as well as challenges faced with staff retention.

Table 5. Reflections on hiring and retention of NACP extension staff

Action Item	Hiring of Climate Mates	Retention of CM/Extension Staff
First Try (2018-2020)	CM Positions were advertised on Seek, USQ website, NRMJobs, and similar. CM were hired based on local knowledge and networks	Climate mates were recruited for one day per week
First Try Reflection	Recruiting in remote areas was difficult, and many producers do not look at Seek/USQ website for jobs. Putting an ad in a newspaper (eg QLD Country Life) proved cost prohibitive. Regardless, applicants were of high quality and NACP was able to fill the 8 CM positions.	One day per week and being project work, therefore not permanent, retention has been an issue
Second Try (2020-2022)	In 2020, the number of CM was doubled, requiring further recruitment. A number of sub-contracts with NRMs were pursued and approved. Job positions were advertised in the previous channels and were also	We have partnered with some NRM groups to deliver in some areas, meaning we have half our Climate Mates working for NRM groups and half as Producers.

	advertised in local community or council newsletters	
Second Try Reflection	Sub-contracting some of the CM positions to NRM groups removed the stress and time sinks around new hires. Advertising in regional newsletters proved beneficial. Again, there were few applicants, but those who did apply were of high quality.	This has worked in that retention of staff has been better. It still requires some fine tuning. Loss of Climate mates will be an ongoing issue in some areas.
Future Advice	Advertising in regional newsletters is cost efficient and reaches many producers in remote areas. Embedding a CM with an NRM role eliminates the need for NACP to go through the rehiring process if a CM leaves the position, which saves considerable time and resources.	Mitigating lost information and time is one strategy we would like to address in the future. This will help with a central CRM system, meaning notes and information can be passed on accurately and the downtime of the new Climate mate will be less. We also would like to improve new employee training as mentioned to get extension staff up to speed faster.

Climate Mates as Producers or in an NRM Role

Approximately half of the current Climate Mates are producers and the other half work for an NRM group. Below outlines the benefits of each.

Benefits of Climate Mates who are also producers:

- Established within the local producer community – Already know neighbours and 'key players' in the region
- Can use forecast information for their own property and then demonstrate to other producers what they have done – this is critical for developing producer trust
- Have a wealth of property management knowledge, which makes it easier to see how weather/climate information and forecasts 'fit in'
- Can hold on-property events that include live demonstrations (such as forage budgeting) that complement the climate component.

Benefits of Climate Mates who also work for an NRM:

- **Context & Relatability**: Local NRMs are well versed in the regions land management practices and animal production systems. The Climate Mate can provide climate information within the context of the local region in a way that relates it to relevant practices, issues and opportunities.

- **Upskilling & Education of regional extension officers**: 'Train the Trainer' approach – The entire NRM organisation enjoys the benefits of having an embedded Climate Mate.

- **A Trusted & Local Organisation:** A the local NRM group is a well-known and trusted advisor in the region, and has been for many decades. The Climate Mate is able to benefit from this to get a 'foot in the door' when it comes to engagement. Also, NRMs are typically seen as objective and impartial which allows them to connect across different stakeholders – pastoral, indigenous, departments, private companies from mining through to not-for-profits and other local groups, and the NACP program can leverage this local reputation.
- **Collaboration & Value Adding**: Local NRM organisations already run numerous events, activities and projects to which NACP can either collaborate or value add rather than working independently. This may be as simple as getting a speaking position at a field day being put on by another project, or could be a more elaborate collaboration where the Climate Mate coordinates with an organisation such as DAF to design an event that integrates Season Climate Forecasting with Grazing Land Management. An NRM Climate mate is engaged with local producers on other projects which then allows them additional engagement opportunities with producers/extension staff on more of a larger part-time or full-time basis, more so than the 0.2FTE allocation of time
- **Internal & In-Kind Support**: NRMs offer significant in-kind support such as vehicle use, without which NACP would incur a significant cost, office use (including printing), and other workplace support NRM organisations enjoy internal support when it comes to administration, event planning, comms, budgets, and so on. This lessons the load on the Climate Mates particularly in terms of admin and logistics, allowing them to spend more time on activities and tasks that create practice change. NRM organisations will also likely have subject matter experts in agriculture that would be able to assist a Climate Mate that may not have skills in this industry. Other NRM officers could provide support on grazing and animal production issues that would be beneficial.
- **Existing Networks & Relationships:** NRMs have access to a comprehensive mailing list, reach in terms of social media, and an ability to attract interest in local events.

Training

The NACP training program, including initial, annual, and ongoing training, constantly evolved during NACP2. Feedback from the Climate Mates went directly into this evolution. Table 6 outlines how and why Climate Mate training changed during NACP2.

Table 6. Reflections on NACP Climate Mate training, including initial, annual, and ongoing training.

Action Item	Providing in-depth climate training to climate mates to prepare them for their role	Training for Climate Mates at annual meetings	Ongoing Training for Climate Mates
First Try	Climate Mates attended a 5-day training session in Toowoomba, with climate information presented by the BoM	Reviewed all climate info presented at initial training.	After the initial training, further questions or training were mainly handled on an individual basis, either over the phone or when meeting in person for NACP workshops and events

First Try Reflection	Pros: Beneficial for Climate Mates to get together in one place, along with the BoM, right at the start to allow for connecting and networking. Cons: Five full days of climate training by the BoM was too much and many Climate Mates felt totally overwhelmed. Information was presented at a level far above what it should have been. Training needed to include more explanation of how to do extension work (e.g. how to organise a workshop; how to meet with producers one on one) and more review of online tools	Climate Mates definitely needed to review the climate information after the (too) intense initial training; Also needed to review reporting and how to use USQ systems (e.g. travel). One day was not enough time and many discussions had to be stopped	Climate Mates all claimed to learn a lot every time they put on or attend a NACP workshop or event where senior members of the NACP extension team are presenting. However, it was clear more regular training was needed after the initial training
Second Try	Due to COVID, the second round of Climate Mate training (for 8 new hires) was provided entirely online. A video series was produced by NACP and the BOM that aimed to deliver the climate information in an easy-to-understand way. There were also videos on how to do extension work. Zoom meetings were held twice a week for 4 weeks to allow for discussion of videos. BoM attended these Zoom meetings	Review climate information including latest research by NACP/BOM. Climate Mates were tasked with reviewing a website (or idea) and then they presented back to the group. One and a half days was not enough time.	Zoom meetings that included the NACP/BOM employees were held to continue to upskill Climate Mates, even when COVID prevented travel.

Second Try Reflection	Pros: Climate Mates preferred this style as it allowed them to process the information over a longer period of time and reflect on what they learned. Also, the information was less technical. Cons: Not meeting in person limited development of networks and connections between CM and BOM; One hour Zoom sessions not long enough to cover all topics; Unable to know if CM actually watched videos	Tasking the Climate Mates helped facilitate deeper and group learning as well as providing relevant experience they need when interacting with producers. This was much better than simply having a climatologist explain things. It would be nice to have two full days at meetings every year, however, this isn't necessarily practical.	These Zoom meetings were well received and CM requested that they occur more frequently. Not all CM could attend all Zoom sessions, which could possibly lead to some CM having gaps in knowledge.
Future Advice	A mix of Zoom and in-person training would be ideal for the future. CM would first watch videos and have short Zoom sessions. This would be followed closely by an in-person 3-day training. Additionally, this in-person training would need to include a mock half day workshop to allow new CM to see how to conduct a workshop and what delivery methods are most effective.	Always task the Climate Mates with something they need to present on that will help them with their role. A second training during the year would help ease trying to fit everything into the annual meeting.	CM would benefit from hosting one NACP event (such as a workshop) per year to catch up with senior NACP extension staff face to face. Zoom meetings that include NACP/BOM should be held approximately once per quarter

Activities

The NACP extension team worked together to carry out NACP-related activities that contributed to KPI gains. NACP workshops involved a Climate Mate supported by the NACP climatologist, while other events, such as multi-topic events with short speaking slots (less than 30min) were carried out either by the Climate Mate or the climatologist, depending on content. One-on-one activities were usually carried out by the Climate Mate alone. Table 7 shows a selection of NACP extension activities, with numbers reflecting activities undertaken from 1 March 2018 to 1 January 2022. Note that social media does not allow the differentiation between 'Producers' and 'Others'.

NACP climate workshops incorporate climate driver information relevant to the region, provide by-region management applications, and usually include a NACP/BOM representative. Providing these workshops gives the following benefits which align with meeting KPIs:

- Providing regionally-relevant climate information to producers
- Increasing knowledge, skills, and awareness, Category B
- Creating a relationship with producers that is likely to lead to Category C goals
- Fostering a relationship between the Climate Mate and the BOM
- Providing feedback from the producers to the BOM
- Showing producers new prototype tools and products being developed as a part of NACP.

Table 7. Selection of main NACP extension activities between 1 March 2019 and 1 January 2022, including number of producers and 'others' reached

Activity Type	Number of Activities	Total People Reached	Producers	Others
NACP Climate Workshops	48	559	346	210
Presentations (at multi-topic workshops, field days, etc)	206	5,241	2,603	1,991
Phone Calls/Emails	247	7,686	4,206	2,430
One-on-one / On-Property Visits	127	393	309	84
Meetings with Other Extension Specialists	42	290	126	168
Social Media	378	26,101		
Webinar	21	421	128	195
Total	1,069	40,691	7,718	5,078

NACP extension activities evolved during the project. Initially, NACP Climate Workshops were pursued as the main mechanism to accomplish KPIs. However, it quickly became clear that partnering with other groups for activities allowed NACP to reach more producers and was more cost/time effective (Table 8). For example, inviting a speaker from Queensland Department of Agriculture and Fisheries to present on pasture management at a NACP workshop allowed the NACP climate information to be presented in an applied way and attracted broader interest than climate information alone. Another example is being invited by the Rural Financial Councillors (RFC) to join them for two roadshow, multi-topic events and the RFCs paid for NACP expenses and had a large audience due to the quality of speakers and topics provided.

Table 8. Reflections on NACP Climate Workshops and Co-organised events.

Action Item	NACP Workshop Structure	Multi-topic /Co-organised events
First Try	8am to 3pm; Very climate heavy with workbook focussing on things like how to read SOI/SST charts	Organised NACP workshops, with few other events
First Try Reflection	Producers found the information to be interesting, but many also felt overwhelmed. Producers received very little information on how to use this information (just a piece of butcher paper with a list on it)	KPIs were originally based on presenting NACP workshops, so this was the initial focus. However, it was very time/cost intensive to provide NACP-only events and number of participants was sometimes lower than desired.
Second Try	8am to noon or 2pm; Much larger focus on where to find forecasts, how to apply this information - workbook reflects this. We try to have an outside speaker on a related topic (ie weed control)	After the first year, NACP became better known and started to be invited to events hosted by other groups. Additionally, NACP started inviting speakers on related topics (ie pasture management) to NACP workshops so that producers could understand how to apply the climate information to other topics.
Second Try Reflection	Practice change requires that producers have a clear understanding of how to use the information, so the change to more applied workshops is beneficial for meeting practice change goals. Workshops still likely have too much content and the half day format may be too long for many producers - it's very hard for people to take in that much information	Multi-topic days, field-days, etc are generally better attended than a stand-alone NACP workshop. Thus, presenting at co-organised events allows NACP to reach a broader audience. The main drawback is that NACP isn't always giving a long speaking spot and that NACP cannot have its own feedback sheet (usually only the organiser gets a feedback sheet). Having an outside speaker at NACP workshops helped increase attendance and break up the day
Future Advice	Workshops need to take application a step further and get producers to commit to a specific action (ex. check seasonal forecast) at a specific time (ex. first Monday of the month during morning tea). Development of a annual planning calendar would benefit the program.	If there is a strong demand in an area for a NACP workshop, they are worthwhile. However, it can be hard to get people to attend a NACP workshop, though having an outside speaker on a popular topic can assist with this. Speaking at events organised by another group is a cost and time effective way for NACP to reach a broader audience, though the trade-off

		is that NACP may not be able to have their own feedback sheet and/or they may not have a lot of time to talk. Both NACP workshops and co-organised events need to be pursued equally in the future.

NACP extension presented at conferences, the largest being Beef Week held every three years in Rockhampton, Queensland. Presenting at large conferences increased awareness of NACP and facilitated conversations with other attendees. A list of conferences attended can be found in Table 9.

Table 9. Conferences attended and provided presentation(s)

Conference, Location	**Year(s) attended**
Beef, Rockhampton, QLD	2018, 2021
Northern Territory Cattlemen's Association, Alice Springs, Darwin, NT	2021, 2022
Australian Meteorological and Oceanographic Society, Darwin, NT; Fremantle, WA; Virtual	2019, 2020, 2021
Australian Rangeland's Society, Longreach, QLD	2021
Protein, Roma, QLD	2021
Tropical Agriculture, Brisbane, QLD	2019
Young Beef Producer's Forum, Roma, QLD	2021
International Biometeorology, Virtual	2021
Bureau of Meteorology, R&D Workshop, Virtual	2020

Benchmark Surveys

Surveys of the Climate Mates were conducted in 2019 and 2021 to collect feedback as to how the Climate Mates found their role, including likes and areas for improvements. Some of this feedback has been included in the 'Reflections' tables, listed previously in this report, such as the Climate Mate's feedback on the initial climate training. Feedback was used to improve the NACP extension program and Climate Mate experience. There were no drawbacks to conducting these surveys as the Climate Mates were able to fill them out online into a database that automatically generated a report. Full reports of the surveys can be found in Appendix E.

NACP3 will continue with issuing benchmark surveys every 18 months to ensure the program is meeting Climate Mate needs and to identify any areas needing improvement.

16.5 Conclusion

NACP extension was successful in meeting and exceeding all contractual KPIs and milestones. Being closely linked with NACP R&D and the structure of the extension team, including a climatologist, a pastoral production expert, an agriculture/marketing expert and the Climate Mates, were critical to this success, as the variety of experiences and knowledge contributed to improve NACP.

16.5.1 Key findings

The key findings of NACP extension are as follows:

- The NACP RD&E model was critical for the success of the NACP extension team due to the communication and support offered by BOM/UKMO R&D
- The two-way flow of information between producers and R&D via the Climate Mates led to producer-driven tools being created and then communicated back to the producers
- The Climate Mate model was successful in accomplishing meaningful extension work
- Extension programs need to constantly be reviewed and updated to best accommodate producers and include the latest research
- Having Climate Mates who are producers or also work for an NRM was beneficial in allowing the program to meet its goals and have a diverse group for knowledge sharing
- Social media was a useful way to reach more producers and attract producers to NACP events
- Having a variety of communications tools (videos, newsletters, social media posts, booklets, etc) ready to go was required to effectively communicate with producers
- Presenting climate information in an applied context was critical for producer uptake
- It can be difficult to collect specific practice change metrics (economic, environmental, social).

16.5.2 Benefits to industry

The NACP extension component benefitted the red meat industry. Conservative estimates are that 1,509 producers learned a new skill or gained knowledge because of NACP, with 888 ‘others’ (including supply chain and related groups such as NRMs) also increasing KASA. It is important to remember that many of the ‘others’ regularly work with producers and can pass on information learned from NACP. Impressively, 161 producers reported making a management decision based in part on information provided by NACP while an additional 70 producers reported that they now regularly look at forecasts and/or regularly use tools shown to them by NACP extension.

Producers using forecasts and climate tools benefits the industry in the following ways:

- Increased producer awareness of likely coming dry or wet conditions, which triggers management decisions
- Management decisions made early, especially the decision to sell if dry conditions are imminent, lead to improved financial, environmental, animal welfare, and social (less stress) outcomes
- Being able to recognise a ‘dry forecast’ and evaluate pasture condition and number of stock is critical to improving industry outcomes
- Deeper producer understanding of what ‘normal’ weather and climate is for their region, which leads to better planning

Another major benefit is the legacy that the Climate Mates have in their community. From 2019-2022, eight Climate Mates quit the role (usually due to taking a full-time role elsewhere). NACP has kept in touch with these Climate Mates and the majority are continuing to use their climate information in their community and in their new job.

16.6 Future research and recommendations

- Future extension programs should consider a 'Climate Mate' structure as a way to quickly connect with producers
- Linking R&D with extension is critical to ensuring that the R&D meets end user needs
- Collecting data during extension can be challenging – having a robust, easy-to-use reporting system in place is necessary to collect detailed metrics
- MLA needs to invest in researching ways to capture the metrics they want and then pass this information on to the program – not rely on the program to develop something, as developing these methodologies takes considerable time and specific expertise
- Use of social media, especially Facebook, is a cost-effective way to advertise events and reach producers
- Creating online content (videos, webinars, etc) allows extension to better service remote areas and also to continue even when people cannot travel

16.7 References

Cobon David, Jarvis Chelsea, Reardon-Smith Kate, Guillory Laura, Pudmenzky Christa, Nguyen-Huy Thong, Mushtaq Shahbaz, Stone Roger (2021) Northern Australia Climate Program: supporting adaptation in rangeland grazing systems through more targeted climate forecasts, improved drought information and an innovative extension program. *The Rangeland Journal* **43**, 87-100. https://doi.org/10.1071/RJ20074

Hewitt, C. D., Stone, R. C., and Tait, A. B. (2017). Improving the use of climate information in decision-making. *Nature Climate Change* **7**, 614–616.

16.8 Appendix

Appendix A: MERI Plan, Updated 1 March 2022

Appendix B: COMMS Plan, Updated 1 March 2022

Appendix C: List of Narratives to 1 January 2022

All NACP Narratives.xlsx

Appendix D: Impact Assessment Case Studies

NACP 2 Case Studies_Sml.pdf

Appendix E: Climate Mate Benchmark Survey Results

Sample Survey	2019 Results	2021 Results
Climate Mate Benchmark Survey	2019_ClimateMate_Benchmark_Survey.pdf	CM_Benchmark_Review_2021.pdf

17 Other products – extreme heat and cold

David Cobon[1], Thong Nguyen[1], Tim Cowan[1,2], Cat de Burgh Day[2], Deb Hudson[2]
1 University of Southern Queensland, Toowoomba, Queensland, Australia
2 Bureau of Meteorology, Melbourne, Victoria, Australia

17.1 Background

Extreme heat load in grazing livestock in Australia already can cause significant calf (15%) and cow (8%) wastage (McGowan et al. 2016, McCosker et al. 2020) reduced feed intake and production. Increasing and more extreme temperatures and a higher proportion of Bos taurus genetics in herds is likely to cause more serious losses in future. Production and welfare issues caused by extreme heat events are major concerns to the beef and dairy industry supply chain, particularly on property and in the livestock transport areas. Forecasts of heat that already exist such as maximum temperature don't reliably identify the extreme heat events that cause severe impacts on cattle because other variables such as humidity, radiation and wind can significantly exacerbate or mitigate high temperature impacts. Forecasts have not been developed that include all these critical components nor do multi-time scale forecasts of indicators at critical thresholds exist for cattle (grazing, feedlot, dairy)

Exposure of animals to cold, rain and wind during the Gulf flood event in February 2019 is believed to be a significant factor contributing to livestock losses. The unprecedented event was described as Australia's worst livestock disaster and was characterised by extreme rainfall, low maximum temperatures and strong winds that caused widespread cattle mortality with reports of over 500,000 head dying mainly from drowning, hypothermia and pneumonia. Overall costs associated with on-property losses, including livestock and infrastructure, were estimated at $5.68 billion. Some 800 properties were affected over 13.25 million hectares – an area twice the size of Tasmania. (Deloitte 2019; Agro Insurance International News https://agroinsurance.com/en/australia-cattle-deaths-5-billion-loss-largely-uninsured/. The flood impact on the Gulf Plains pastures was initially severe and surface sheet erosion between tussocks was widespread (Hall 2020).

17.2 Objectives

Develop prototypes of indicators that can effectively monitor and predict heat and cold for grazing livestock in northern Australia.

17.3 Methodology

The temperature humidity index (THI) thresholds of >80 negatively impact Bos taurus breeds but thresholds for Bos indicus cattle maybe higher (e.g. 90). The THI is defined as:

$THI = Tmax + 0.36 * Td + 41.2$, where Tmax is daily maximum temperature, Td is daily dew point temperature and,

$Td = (234.5 * f(VP)) / (17.67 – f(VP))$, and

$F(VP) – In(VP / 6.112)$ and VP is mean of 9am and 3pm vapour pressure.

A simple to implement chill index that nominally measures the hourly heat loss from animals (Carter et al 2019, Nixon Smith 1972, Donnelly 1984) has been developed for sheep in southern Australia.

This chill index formula calculates the potential heat loss (C) in $kJ/m^2/hr$ using mean daily wind velocity (v; m/sec), the average daily temperature (T, °C) and daily rainfall (x; mm) as below:

$C = (11.7 + 3.1v^{0.5})\ (40\text{-}T) + 481 + (418(1\text{-}e^{-0.04x}))$.

The comprehensive climate index (CCI) is a linear combination of ambient temperature, corrected relative humidity, corrected solar radiation and corrected wind speed, based on Mader et al. (2010), and applied at ambient temperatures of 5°C and over. The wind chill index (WCI) is a linear combination of temp and windspeed and their coefficients (Tew et al. 2002) and applied when the temperature is below 5°C.

The daily data from SILO used to compute the comprehensive climate index (CCI) include: Temperature (max & min): ^{0}C, 0.05^0, Relative humidity (max & min): %, 0.05^0, Solar radiation (RAD): W/m^2, 0.05^0, Wind speed (WS): m/s, 1^0. The CCI is defined as (Mader et al. 2010):

$CCI = Ta + RH_{cf} + WS_{cf} + RAD_{cf}$,

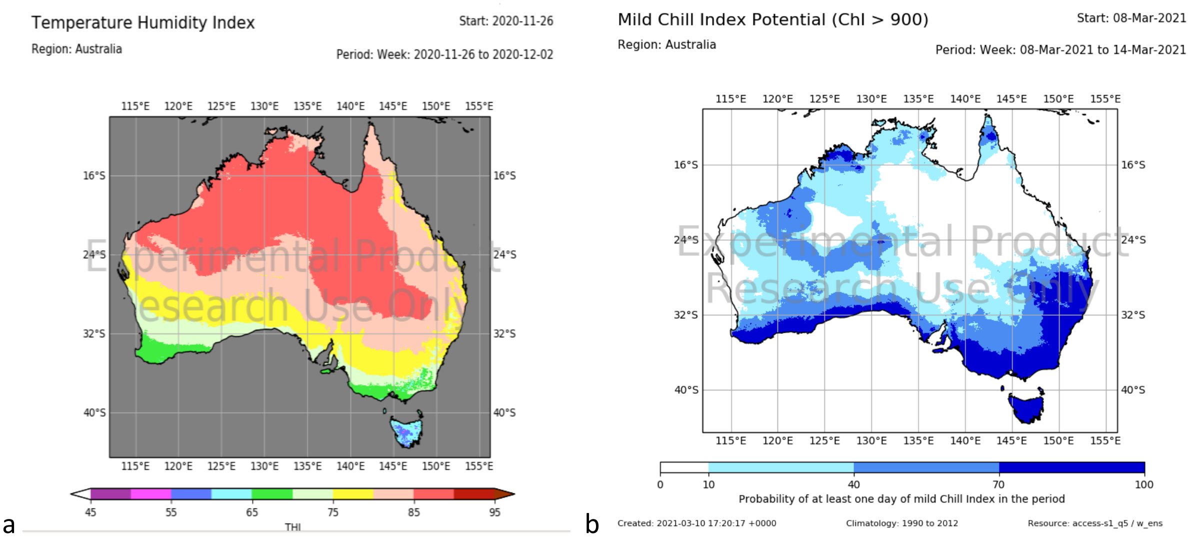
where RH_{cf}, WS_{cf}, and RAD_{cf} are RH correction factor, WS correction factor, and RAD correction factor.

17.4 Results

The temperature humidity index (THI) has been produced as a prototype product that can provide a spatial indication of the extent of heat and humidity (Fig 1a).

The Chill Index has also been produced as a prototype product for mild (900-100 $kJ/m^2/h$ heat loss) (Fig 1b), moderate (1000-1100), high (1100-1200) and severe (>1200) levels of heat loss.

Figure 1. Prototype products of the a) temperature humidity index and b) forecast of mild chill index potential from the NACP FVT prototype website.



The uptake of the THI by producers has been slow possibly because of its low relevance (predominance of work in dairy in southern Australia and few studies in the north) and accuracy for northern Australia grazing conditions. The heat load index (HLI) is considered a better indicator of livestock stress impacts than THI because it also includes solar radiation and wind which have significant additional effects in northern climates – for example, an accumulated THI (for a few days) of 90 without wind and with high solar radiation could cause considerable production losses and welfare issues, but potentially considerably less with wind and low radiation.

17.5 Conclusions

17.5.1 Key findings

The heat load index (HLI) or Comprehensive Climate Index (CCI) are considered better indicators of livestock stress impacts than THI because they also include solar radiation and wind.

17.5.2 Benefits to industry

Climate forecasts of combined indices (e.g. temperature, humidity, wind direction and solar radiation) would support more informed and timely management decisions regarding heat at relevant locations.

17.6 Future research and recommendations

Develop a heat load index that includes wind, solar radiation.

Further develop and evaluate the Chill Index (or Wind Chill Index) for cattle in northern Australia because the risk of extreme cold will be higher in a future climate.

17.7 References

Carter, J, Bruget, D Stone G (2019). Exposure as captured by a chill index as a contributing factor to livestock losses in Northern Queensland. Department of Environment and Science, Brisbane (unpublished notes).

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Nixon-Smith WF (1972). The forecasting of chill risk ratings for new born lambs and off-shears sheep by the use of a cooling factor derived from synoptic data. *Working paper 150, 40/145 of April 1972, Bureau of Meteorology, Australia*.

T. L. Mader, L. J. Johnson, and J. B. Gaughan (2010) A comprehensive index for assessing environmental stress in animals. J. Anim. Sci. 2010. 88:2153–2165, doi:10.2527/jas.2009-2586

Tew, M., et al. (2002). Implementation of a new wind chill temperature index by the National Weather Service. INTERNATIONAL CONFERENCE ON INTERACTIVE INFORMATION AND PROCESSING SYSTEMS (IIPS) FOR METEOROLOGY, OCEANOGRAPHY, AND HYDROLOGY.

18 Reviews of research, development and extension

Research was reviewed by Dr John McBride in September 2019 and October 2021. Development and Extension was reviewed by Coutts Consulting in October 2021. A summary taken from these reports follows. The full review reports are provided in Appendix.

18.1 Review by agreed reviewer Dr John McBride (October 2021)

The summary evaluation is that the science is of the highest standard. It is internationally leading and internationally recognised, and it is directed towards the needs of the grazing industry. The project description of improving the basic science and operational forecast skill is ambitious but has been achieved.

The program has made a number of significant and important scientific achievements. These include 1) Development of specialized forecast products tailored to the grazing industry, 2) Demonstration of skill in forecasting ENSO (El Nino-Southern Oscillation) events up to 18 months ahead, 3) A fundamental change in the methodology of adapting the UKMO dynamical model for the Australian operational forecast model, 4) Development of partnerships connecting climate, agricultural research, extension and adoption practitioners, advisers and producers, and 5) Forty publications prepared for or published in the international refereed scientific literature.

Continuation of the project into a third phase NACP-3 is supported and recommended.

The infrastructure of the project is centred on the Bureau of Meteorology forecast model for multi-week, seasonal and longer-term weather and climate forecasting. The model has the name ACCESS-S1 (or in later developments S2, S3) and is a “coupled” atmospheric and oceanographic dynamical forecast model. The model ACCESS-S is the result of an ongoing partnership between the Bureau of Meteorology Australia (BOM) and the United Kingdom Meteorological Office (UKMO), whereby the dynamical model is a recent version of the UKMO coupled model, known as GC (for Global Coupled) UKMO-G with a version number. The BOM ACCESS-S model runs the UKMO-GGC model, but under local configurations of initial conditions, dynamical initialization procedures, method for carrying out ensemble forecasts, methods of integrating satellite-based remote sensing observations, and other local enhancements and redesign elements.

The objectives of the current research program have several components: a) improving the skill of forecasts, b) advancing fundamental knowledge of the mechanisms governing predictability and drought, c) the development of forecast products tailored to the requirements of the grazing industry. The overall assessment is that all objectives were ambitious and have been achieved. In the relatively short period of the program, it has made a number of significant and important scientific achievements. All of these are the result of the research sub-project NACP-P1. All are of tangible benefit to the grazing industry, and all would not have occurred without the NACP program. They include the following:

- Development and/or improvement of specialized forecast products tailored to the grazing industry, including Northern Rainfall Onset and rainfall bursts.
- A demonstration that the coupled dynamical forecast models have good skill in forecasting ENSO (El Nino-Southern Oscillation) events up to 18 months ahead
- An improved understanding of forecast issues from case studies of the February 2019 flood event which resulted in huge losses of cattle and other livestock.

- A fundamental change in the methodology of adapting the UKMO dynamical model for the Australian operational forecast model.
- An important NACP contribution to the development of the new convection parameterisation scheme for the UKMO dynamical model
- From an a priori state of no research on flash drought in Australia, flash drought indices have been developed and both monitoring and short-term and longer-term forecasts of flash drought are now run operationally routinely as a prototype.
- Fundamental research has been carried out into mechanisms causing drought in Australia.
- Partnerships have been developed connecting climate, agricultural research, extension and adoption practitioners, advisers and producers.
- From NACP, 40 publications have been prepared for or published in the international refereed scientific literature.

Several factors were identified that should bring about an increase in the accuracy of forecasts:

- The change in methodology such that there is now direct involvement in the ongoing research at the UKMO to improve, upgrade and evaluate the dynamical forecast model. This results from the NACP staff embedded at the UKMO, the consequent change in the nature of the UKMO-Bureau of Meteorology modelling partnership, and the appointment of two senior Bureau of Meteorology staff to major decision-making committees in the UKMO forecast modelling infrastructure
- The development of the new cumulus parameterisation scheme COMORPH, which from current test forecasts and hindcasts will bring about a measurable increase in accuracy
- investment in fundamental research on predictability
- the large scale of the investment such that the focus and priorities of the major institutions are more directed to longer term forecasts and to the tropical regions.

The review endorses the program of research in the proposed follow-on NACP3 project. The objectives are appropriate and are directed towards carrying the research of NACP2 (the current NACP) through to a stage where the benefits can be maximised. One of the key factors is the long-time frame of model dynamical forecast model development, and the fact that the new findings and model improvement from NACP2 can be incorporated into the operational forecast within the timeframe of NACP3. I endorse the focus on model improvement and improvement in model forecast accuracy. I also endorse the further exploration of the feasibility of multi-year forecasts. A strength of the NACP2 was that it included a large research component directed at understanding of the physical mechanisms causing drought and the mechanisms governing predictability of climate influences such as ENSO. It is pleasing to see this will be continued through NACP3. Based on the NACP2 findings, there are some new areas of emphasis in theNACP3 proposal. In particular, there is a greater emphasis on the understanding the mechanisms causing drought, rainfall variability and the predictability of drought. There is also a new emphasis on case studies of major events.

18.2 Review of development and extension by Coutts Consulting (October 2021)

This program has clearly made a significant contribution to developing more effective rainfall and climate related decision tools for graziers across northern Australia. However, should the program end now then much of the momentum and legacy would be lost – with unfinished outputs, limited extension capacity and slow uptake of products developed. What is needed is more effective strategic and targeted extension involving Climate Mates and other extension deliverers to address the lacks in reach, awareness, understanding and effective use of available outputs.

Recommendation 1 - The NACP program needs to continue to build on the excellent foundations that have been established to ensure that the new and improved development forecast products are properly tested, refined and established in the decision-making framework of users across northern Australia.

Recommendation 2 - As well as providing a testing ground for research through Climate Mates, a strong focus for the next phase of the program should be on collecting post activity impact metrics to reach more users, raise awareness and understanding of forecast products and encourage their effective use in decision-making.

Recommendation 3 - As part of developing an Extension Strategy for the next phase of NACP, the program needs to clarify its purpose, collaborators, priority user segments, targets and develop a Monitoring, Evaluation and Learning Plan.

The deployment and support of Climate Mates makes total sense in terms of including local experience and trusted sources – both in the development and extension process. In practice, the experience to date has demonstrated that these benefits can be realised through an effective and supported network of Climate Mates.

The question will be around numbers, criteria, locations, time allocation, expectations, training and support. It is acknowledged that the current CMs have good regional coverage across northern Australia however they are limited in how much they can realistically work with (other) producers under the current conditions (e.g. limited time and large distances).

Recommendation 4 - Climate Mates would be an essential part of another phase of NACP with a need to maximise their contribution through allocating extra time, having links to extension organisations, building relationships with extension deliverers and having structured frameworks to assist their engagement with more producers.

With an increased emphasis on extension, capacity building and practice change a comprehensive evaluation framework needs to be in place to guide the process and more effectively report change and impact. Having a clear focus and well formulated extension strategy and targets, provides a stronger basis for evaluating and reporting on impact. The broader user group level requires the use of structured feedback at face to face and online activities in relation to increasing awareness and learning, as well as periodic follow-up in terms of measuring the type and extent of use in decision-making and practice change and the benefits being gained.

Recommendation 5 - Effective monitoring and evaluation will require a process for capturing post-activity impact on participating producers and other user segments at an individual and broader group perspective. This will require producers to be aware of the need for this evaluation and to be invited to participate in the process.

18.3 Review by agreed reviewer Dr John McBride (November 2019)

The research was described as well thought out and world leading with a high level of interaction between the research, development and extension components. The research leadership within the

Bureau of Meteorology team is world leading and described as one of the major reasons for the high level of success of the research component.

The following recommendations were made:

1) The NACP research programme should be continued with a follow-up four-year programme to reap the benefits of the focus on forecasting for Northern Australia. To maintain the high level of success it will be vital that these components be included in any follow-up or extension project the:
    - placement of scientists within the UK Meteorological Office
    - theoretical (or understanding focused) component which is advancing knowledge and of Northern Australian monsoon mechanisms and variability
    - seniority and world-leading expertise of the key scientists
    - consideration should be given to placement of a third NACP scientist in the UK Meteorological Office.
2) Consideration should be given to a greater emphasis on the underlying mechanisms of drought in the research component of NACP.
3) The current NACP research focus should continue development work on the current three forecast time scales: one week to a month, seasonal, and multi-year forecasts.
4) Consideration should be given to an increased research focus being directed to the seasonal predictability of high impact short time-scale major events such as tropical cyclones, rain-bearing monsoon lows and flash droughts.
5) Consideration should be given to a higher level of financial support for the multi-decadal forecast development. While the level of possible skill or theoretical predictability is still unknown, the multi-decadal research has the potential of a revolutionary change in seasonal forecasting for agriculture.

The project proposal for NACP3 includes all recommendations from these reviews.

18.4 Appendix

APPENDIX A – Research review Dr John MCBride - October 2021

REVIEW NACP
Research project P1 C

APPENDIX B – Development and Extension Review, Coutts Consulting – October 2021

DAF NCAP - Review
Report October 2021

APPENDIX C - Research review Dr John MCBride - November 2019

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19 Publications

NACP Publications – published, submitted or in-preparation (17 March 2022)

No	Short title	Title	Authors	Journal / Pub date
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 forecasts in the northern Australia beef industry	Cobon, Darbyshire, Crean, Kodur, Simpson, Jarvis	WCAS 12, 3-14 (2020) https://doi/pdf/10.1175/WCAS-D-19-0018.1
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	Nguyen T, Kath, Mushtaq, Cobon, Stone G, Stone R	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	Value of seasonal rain	Regret function approach to quantify the value of seasonal precipitation forecasts in regional beef cattle production systems in Northern Australia	An-Vo, Cobon, Reardon Smith	In prep
11	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
12	Simulation of Tropical cyclone genesis in Aqua-planet configuration	Real world and tropical cyclone world. Part II: sensitivity of tropical cyclone formation to uniform and meridionally-varying sea surface temperatures under aquaplanet conditions.	KJE Walsh, **S. Sharmila**, M Thatcher, S Wales, S Utembe, A Vaughan	J. Climate, 33, 1473-1486 (2020) https://doi.org/10.1175/JCLI-D-19-0079.1
13	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
14	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
15	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
16	Walker circulation	Walker circulation sensitivity to extratropical radiative forcing	Kang, Xie, Shin, Kim, Hwang, Stuecker, Xiang, Hawcroft	To be submitted to *Nature Climate Change*
17	Accumulated rainfall in tropical cyclones	Global climatology of rainfall rates and life-time accumulated rainfall in tropical cyclones: Influence of cyclone basin, cyclone intensity and cyclone size	Lavender,SL, McBride, JL	Inter. J. Climatology 2020; 1-19 https://doi.org/10.1002/joc.6763

18	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
19	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 doi:10.1175/JCLI-D-21-0264.1
20	Developing a combined drought indicator	Developing and evaluating the combined drought indicator (CDI) for Australia	Nguyen-Huy, T., Guillory, L., Pudmenzky, C., Cobon, DH	In prep
21	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
22	Northern Australia Climate Program	Northern Australia Climate Program - Supporting adaptation in rangeland grazing systems through more targeted climate forecasts, improved drought information and an innovative extension program	David Cobon, Chelsea Jarvis, Kate Reardon-Smith, Laura Guillory, Christa Pudmenzky, Shahbaz Mushtaq, Roger Stone	Rangelands Journal – invited special issue on drought – Sept 2021, https://www.publish.csiro.au/RJ/RJ20074
23	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
24	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
25	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,	Bulletin of the American Meteorological Society (BAMS) 2022 .

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26	Value of seasonal forecasts	Economic value of seasonal climate forecasts to the Australian Sugar Industry	Christa Pudmenzky, Rebecca Darbyshire, Jason Crean, David Cobon	Submitted to European Journal of Agronomy
27	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
28	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
29	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
30	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.	*Journal of Climate*, *34*(6), 2205-2218.
31	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	*2021 Weather and Climate Extremes*, 32, 100321.
32	Tropical cyclones	Impact of topography on tropical cyclone formation in idealized aquaplanet general circulation model simulations	Walsh K, S Sharmila, M Thatcher, S Wales, S Utembe and A Vaughan	To be submitted
33	Long lead ENSO prediction	Multi-decadal variability of ENSO predictions in biennial reforecasts of the 20th Century.	Westheimer, A., Balmaseda, M. A., Stockdale, T. N., Mayer, M., Boisseson, E. de, Sharmila, S., Hendon, H.H., Alves, O.	To be submitted

34	Tropical cyclone damage	Estimation of maximum seasonal tropical cyclone damage in the Atlantic using climate models	Lavender, S.L., Walsh, K.J.E., Utembe, S. et al.	Nat Hazards (2021). https://doi.org/10.1007/s11069-021-04977-2
35	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 DOI: 10.1175/MWR-D-20-0330.1
36	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
37	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 (in revision)
38	Long-range ENSO prediction	Contrasting El Niño and La Niña forecast skill in SEAS5-20C coupled model 2-year reforecasts 1901-2010	S. Sharmila, H. Hendon, O. Alves, A. Weisheimer, M. Balmaseda	Journal of Climate (in review)
39	Long-range ENSO prediction	Prediction skill of multiyear ENSO events in ECMWF SEAS5-20C reforecasts over the 20th Century	S. Sharmila, H. Hendon, O. Alves, A. Weisheimer, M. Balmaseda	To be submitted
40	Modelling Maritime Continent weather 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	*Journal of Climate*, *34*(9), 3401-3419.
41	Maritime Continent weather/climate dynamics	The important role of atmospheric rivers in East Asian precipitation trends	Liang, J., Yong, Y., Hawcroft, M.	Climate Dynamics (in revision)
42	Modelling Maritime Continent weather 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.	Climate Dynamics (in review)

43	Flash drought	Climatology and historical occurrences of flash drought over Australia	Nguyen H., Wheeler M. C., Otkin J. A., Nguyen-Huy T., Cowan T.	Journal of Hydrometeorology (in review)
44	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.	Scientific Reports (in revision)
45	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	Bulletin of the American Meteorological Society (accepted)
46	MJO/ENSO impacts	The influence of the Madden-Julian Oscillation and El Niño-Southern Oscillation on Australian seasonal rainfall	Cowan, T., Wheeler M., Marshall A.	To be submitted.
47	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
48	Multiyear prediction	Prospects for 2-year prediction of regional climate	S. Sharmila, H. Hendon, O. Alves, A. Weisheimer, M. Balmaseda	In prep
49	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 Harry H. Hendon	In prep (BAMS)