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A Land of Storms, Floods and Bushfires: Seamless and Integrated Forecasting – Abstracts of the Bureau of Meteorology Annual R&D Workshop, 23 November to 26 November 2020, Melbourne, Australia

Hongyan Zhu, Guomin Wang, Beth Ebert, Diana Greenslade, Catherine de Burgh-Day, Paul Fox-Hughes, François Delage, Carla Mooney, Andrew Frost, Rachel Law, Caroline Poulsen, Mandy Mitreski and Ian Smith
(editors)

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FOREWORD

The Bureau of Meteorology's Annual Research and Development Workshop 2020, the 32nd workshop in the series, has the theme “A Land of Storms, Floods and Bushfires: Seamless and Integrated Forecasting”.

Australia is a land of extremes, and in recent years the country has experienced several high impact weather and climate events. The devastating bushfire season of 2019-2020 and recent mass bleaching events damaging the Great Barrier Reef are just two examples. Improved preparation for the challenges posed by the increasingly extreme environment requires comprehensive, trusted and timely weather, climate and water information to be delivered to the Australian community and business sectors.

Motivated by the release earlier this year of the Bureau of Meteorology Research and Development Plan 2020-2030, this workshop provides a forum for researchers, operational staff and end users to explore innovations and collaborations that enhance our numerical environmental and weather-climate prediction and extreme event forecasting capabilities.

Driven by the demand for risk-based decision-making tools for the protection of life and assets, the rapidly evolving state of high-performance computing infrastructure, and the sharp increase in data volumes, the Bureau’s new Research and Development Plan outlines the following four objectives for the next decade:

- Customised impact-based forecasts and warnings when and where it counts: more localised, timely and better information for cities and regional areas,
- Reliable and trusted forecasts: enhanced assimilation of observations for more accurate predictions,
- An earth system numerical prediction capability: fully integrated atmosphere, ocean, sea-ice and hydrology models,
- Seamless weather and climate insights: historical observations to predictions, from minutes to decades.

The themes of the workshop's daily program are in line with these four research and development objectives and are listed below.

Day 1: Fire, floods and storms: high impact weather and climate
The introductory session focuses on the challenges in seamless modelling development in weather and climate and introduces some extreme events of 2019 in Australia. The bushfire session includes talks ranging from fire ember parameterisation and fire weather prediction to the new Australian Fire Danger Rating System. A session on tropical cyclones includes cyclone formation, cyclone track forecasting and cyclone forecasting strategies. The final session on high impact weather and climate includes talks on volcanic ash forecasts, ENSO and rainfall extremes and drought in Victoria.

Day 2: Bringing extremes into focus: Enhanced assimilation and observation
We start the day with talks on data assimilation covering NWP, ocean forecasting, and coupled systems. The session on convective hazards describes progress in severe weather nowcasting capability at the Bureau, and extreme rainfall in the tropics. The session on observations includes talks on satellite measurement of ocean topography, coastal wave observations and emerging non-traditional observations. High performance computing (HPC) is an essential component of weather and climate R&D infrastructure. In the session on supporting infrastructure, talks on cloud based HPC and the recently announced National Research Infrastructure facility for ACCESS will be presented.

Day 3: Integrated environmental prediction system
Day 3 includes sessions on high resolution modelling, coupled seasonal modelling, ensemble forecasts, and water and climate. Some highlights of the talks include progress and plans on integrated environmental prediction at ECMWF, progress in convection-permitting modelling for high impact weather and climate at the Met Office, global fire weather trends, and big data including weather data applications and the data economy.

Day 4: The future of services
On the final day of the workshop, we hear from leading scientists on what weather predictions will look like in 2030, how climate information helps various industry sectors in Australia, and a historical perspective of the devasting 2019/20 bushfires. The workshop concludes with presentations on societal impact-based forecasting, a major shift from predicting what the weather *is* to what the weather *does.*

We are pleased to welcome a number of international and national experts who have been invited to give keynote presentations relating to the themes.

- Dr Peter Bauer, ECMWF, UK
- Dr Gilbert Brunet, Bureau of Meteorology, Australia
- Dr Andy Brown, ECMWF, UK
- Dr Pep Canadell, CSIRO, Australia
- Lic Julia Chasco, National Meteorological Service, Argentina
- Dr Paul Davies, Met Office, UK
- Prof Mike Flannigan, University of Alberta, Canada
- Dr Michelle Heupel, University of Tasmania, Australia
- Prof Jason Kai Wei Lee, National University of Singapore, Singapore
- Dr Humphrey Lean, Met Office, UK
- Prof Tim Palmer, Oxford University, UK
- Dr Talei Parker, Australian Bureau of Statistics, Australia
- Dr Joanne Robbins, Met Office, UK
- Prof Sonia Seneviratne, ETH Zurich, Switzerland

This year the workshop is held online. We appreciate the willingness of speakers from other time zones to present outside their local office hours. The workshop is sponsored by the Bureau of Meteorology, CSIRO and Hewlett Packard Enterprises (HPE). We would like to thank these sponsors for their generous support of the workshop and in particular, our Gold Sponsor, HPE.

As co-convenors of the workshop organising committee, we would also like to thank the other members of the committee: Rachel Law (CSIRO), Caroline Poulsen (Monash University), and members from the Bureau of Meteorology: Beth Ebert, Diana Greenslade, Catherine de Burgh-Day, Paul Fox-Hughes, François Delage, Carla Mooney and Andrew Frost. Workshop administration was ably provided by Mandy Mitrevski and Tony Baldwin, and Ian Smith is also thanked for his assistance with this book of abstracts.

Hongyan Zhu and Guomin Wang
Research Program, Bureau of Meteorology
Workshop Co-convenors

TOWARD WEATHER AND CLIMATE EARTH-SYSTEM PREDICTION AND INSIGHT

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Over the last decade or so, predicting the weather, climate and atmospheric composition has emerged as one of the most important areas of scientific endeavor. This is partly because the remarkable increase in skill of current weather forecasts has made society more and more dependent on them day to day for a whole range of decision making. And it is partly because climate change is now widely accepted, and the realization is growing rapidly that it will affect every person in the world profoundly through high-impact climate and weather events.

Hence one of the important challenges of our societies is to remain at the cutting-edge of modelling and predicting the evolution of the fully coupled environmental system: atmosphere (weather and composition), oceans, land surface (physical and biological), and cryosphere. This effort will provide an increasingly accurate and reliable service across all the socio-economic sectors that are impacted by weather and climate conditions, whether now or in the future. We will discuss some of the challenges, benefits, and long-term goals of this effort. The talk will aim at a non-specialist audience.

COUPLED FIRE-ATMOSPHERE MODELLING OF EXTREME FIRE EVENTS

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Fire weather forecasts prepared by the Bureau of Meteorology for fire and emergency services agencies address two elements of fire risk assessment. The first relates to seasonal predictions and daily forecasts that are inputs to the landscape-scale fire danger ratings; these incorporate information about antecedent climate at longer time scales and weather parameters at daily time scales and are used for community messaging and warnings as well as agency resourcing, planning and preparedness. The second aspect relates to going fires; once a fire has ignited, in which direction will it spread and how fast? When and where is it expected to impact and what type of fire behaviour is likely to occur?

Coupled fire-atmosphere models address the second risk; the prediction of going fires. The ability to model the coupling process is important because bushfires are not passively driven by weather. Large bushfires release substantial amounts of energy into their surroundings and this alters the environmental wind, which results in interactions between the fire and surrounding atmosphere that can manifest as phenomena quite different from the unaltered state. The interactions can result in rapidly evolving conditions that are hazardous to firefighters and communities.

This talk will describe the coupled fire-atmosphere model ACCESS-Fire; a simulation capability developed using the Australian seamless weather and climate ACCESS modelling system, coupled to a set of fire spread models. Key results from two extreme fire events will be shown; the Waroona fire and the Sir Ivan fire. At both fires, extreme fire behaviour occurred, including rapid spread in a downslope wind regime and development of pyrocumulonimbus cloud; these, and other processes, were well resolved in simulations.

During the 2019-2020 Australian fire season we experienced fires that were unprecedented in scale, but also fire behaviour that exceeded previous experience. ACCESS-Fire is a tool that can be used to simulate the individual fires at critical periods and develop learnings that can be shared with fire meteorologists, partner fire agencies and impacted communities. Planned case studies include: simulating fires that exhibited extreme overnight fire behaviour during heatwaves; fires where fire tornadoes and vortices formed; and fire spread that cannot be reconciled with surface wind observations.

In a changing climate there is growing national and international demand for the knowledge and tools that are required to accurately predict fire impacts. ACCESS-Fire is a capability that has shown skill in capturing the most extreme fire events through implementing complex meteorological inputs and dynamics and there is a strong appetite from our partners in fire agencies to roadmap the potential for future operational use.

A FAST, PHYSICALLY BASED SCHEME FOR PREDICTING LONG-RANGE EMBER TRANSPORT IN BUSHFIRE PLUMES

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In extreme cases, embers transported in a bushfire plume have been documented to start new fires over thirty kilometres ahead of the main fire front (Cruz et al. 2012). Even in less extreme situations, new ignitions a few kilometres away can complicate fire management and create a safety risk. Embers increase the rate of fire propagation and are a major contributor to building loss. The ability to forecast spotfire ignition due to ember transport in fire plumes would assist fire management and improve fire models.

Here, we model ember transport using a bulk model of plume behaviour, accompanied by parameterisations of in-plume turbulence and ember transport and deposition. Although the bulk model is based on the fundamental fluid dynamical equations, it is sufficiently simplified as to be many orders of magnitude quicker to calculate. The results will be compared to those from explicit particle transport calculations from large-eddy model simulations (Thurston et al. 2017), and to available observations.

The ember transport scheme has been coupled to the fire-spread model Spark, which simulates the growth of the fire perimeter using a level-set method (see Cruz et al. 2015 for a review of fire spread equations).

We will present simulations of some significant fires and compare results with and without ember transport. For the Kilmore East fire of 7 February 2009, we simulate maximum transport distances of around 30 km, consistent with that observed.

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THE AUSTRALIAN FIRE DANGER RATING SYSTEM: ACHIEVEMENTS AND CHALLENGES

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Australia is subject to regular fire, and fire danger ratings systems (FDRS) have been developed to better manage its presence in the landscape. For many years, the McArthur forest and grass fire danger rating systems have been used over much of the country to predict the difficulty of suppression of fire, and to identify when it is safe and effective to conduct prescribed burning to manage fuel loads.

In recent decades, however, it has become increasingly clear that the currently used system requires updating or replacement. Much of the Australian landscape cannot be classified simply as "forest" or "grass" and fire danger ratings systems based on those two vegetation types do not adequately predict fire in other environments. Further, advances in fire science cannot readily be incorporated into the McArthur FDRS. The Australian Fire Danger Rating System (AFDRS) is being developed to replace currently used FDRS across Australia.

The project to develop the AFDRS has involved very considerable contributions from a large number of people within the Bureau of Meteorology, from fire agencies, from AFAC (the peak body of Australasian fire and emergency service agencies), and from third-party software developers (who are building the interfaces for several components of the AFDRS). Finally, and importantly, input through fire observations and interpretation has been solicited from fire managers across Australia.

A great deal has been achieved in the four years since the start of a prototype project implemented to test the efficacy of a new system. Highlights include:

- A national fuel map has been developed;
- An end-to-end FDRS forecast system has been implemented nationally, based on eight broad fire behaviour models, and approximately 400 regional and climatic variations across the continent;
- An approximately 20-year reanalysis-based climatology for the AFDRS has been created, characterizing the new system and permitting an assessment of its fitness-for-purpose;
- - Prototypes for three completely new additional indices identifying ignition, suppression and impact likelihoods have been completed;
- A new subseasonal-to-seasonal fire danger forecast module is being developed; and
- The build of a complete operational system is well underway.

Many challenges remain, however. These include: how best to integrate additional information into the system (such as pyroconvective potential); better characterization of fuel moisture content in the fire behaviour models, particularly in the subseasonal to seasonal time frame; and how best to represent ensemble information in the new system.

THE BUREAU'S ENGAGEMENT IN NATIONAL AND INTERNATIONAL SATELLITE ACTIVITIES TO SUPPORT PLANNING, RESPONSE AND RECOVERY FOR BUSHFIRES

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Around 95% of observations assimilated into the Bureau's NWP systems are from satellites, providing the foundation for many of the services delivered by the Bureau, including fire-related weather intelligence for fire agencies and the Australian community. Visible and IR satellite products such as the 10 minute images from Himawari are also used directly by forecasters and fire agencies and are important to support decision making during fire events.

Australia doesn't operate any Earth Observation (EO) satellites. The Bureau has built strong partnerships with international satellite data providers to ensure ongoing access to critical data streams, and to "give back" to the international satellite community through the exchange of science and to capacity building activities. At the national level, the Bureau engages with CSIRO, Geoscience Australia and more recently the Australian Space Agency on activities relating to the exploitation of EO satellites in support of Australian Government priorities. Collaboration builds capacity, enabling each agency to address a small part of the bigger problem, which increases impact for the Australian community.

During the devastating 2019-20 bushfires, the Bureau's international partners, the Japan Meteorological Agency (JMA) and the Korea Meteorological Administration (KMA), generously boosted the Bureau's fire weather services with additional data from their geostationary satellites. JMA provided uninterrupted access to 2.5 minute rapid scan data from Himawari, replacing the regular request arrangement between the Bureau and JMA. KMA also generously provided access to pre-operational 2 minute rapid scan data from GEO-KOMPSAT-2A, as well as providing Australian region fire products on their website.

Following the fires, the Bureau together with other Government and research agencies explored what more could be done to better utilise satellite data in bushfire management activities, including in the pre-fire, during-fire and post-fire phases. The Bureau contributed to the Bushfire Earth Observation Taskforce Report led by the Australian Space Agency, and worked with Geoscience Australia to provide Himawari hotpots for the Digital Earth Australia platform. The Bureau also participated in a SmartSat CRC workshop to explore satellite related research gaps, and contributed Himawari data for the Trillium Data Quest research sprint.

The Bureau is continuing to work with international and national partners on satellite-related solutions in support of fire management. This presentation will provide an overview of the engagement activities from the past year, and explore future opportunities for working with the Bureau's partners to improve satellite data capabilities for bushfire management.

MULTI-WEEK TO SEASONAL FIRE WEATHER PREDICTION AND CUSTOMER APPLICATIONS FOR THE 2020/21 SUMMER

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A new capability has been produced for predicting fire weather conditions more than seven days ahead, with predictions now produced weeks, months, and seasons ahead. Previously, long-range fire outlooks for Australia relied on individual predictions for temperature and rainfall. This new modelling system combines humidity, wind, temperature & rain, together with observations for inputs relating to fuel moisture. This capability has been delivered together with the project partners Bushfire and Natural Hazards CRC (BNHCRC), Victorian Government (DELWP) and the Country Fire Authority (CFA) including strong co-design aspects working with fire agencies throughout Australia.

Since mid-2019, long-range predictions from this project have been delivered to state fire agencies at each of the quarterly meetings and used to prepare the BNHCRC Australian Bushfire Outlooks. These experimental products have provided complementary guidance to the operational temperature and rainfall products for long-range predictions. Delivering long-range fire weather predictions to state fire agencies on this routine (3-monthly) basis has enabled feedback and subsequent tailoring of the products to meet user needs. The project modelling suite and output products provide a foundation that is already being used for next steps in subsequent projects, including the path to operationalisation of long-range fire weather predictions recently started for the new Australian Fire Danger Rating System (AFDRS).

This presentation will show a range of long-range fire weather predictions that have been delivered to fire agencies since mid-2019, including comparing the predictions for the 2020/21 summer with the predictions provided to fire agencies prior to the disastrous 2019/20 summer. The skill of the predictions will be discussed, including details on the physical processes that provide sources of predictability. The output products are designed to be consistent with observations-based data, through the application of quantile-quantile matching, such that they form part of the broader goal for providing hazard information that is as seamless as possible over different time scales. The successful development of this new capability of long-range fire weather predictions means that seamless fire weather products are now available for fire weather products. This includes consistent data sets (0.05 degree grid through Australia for individual days calibrated using quantile matching) for historical records back to 1950 (Dowdy 2018), long-range predictions (multi-week to seasonal as detailed in this presentation) and future climate change projections based on global climate models (Dowdy et al. 2019).

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INCREASING FOREST BURNED AREA IN AUSTRALIA DRIVEN BY CLIMATE CHANGE

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There is ample evidence that climate change has led to increasing fire weather, including an intensification and lengthening of the fire season, in Australia and in many parts of the world. However, there is no evidence that this trend has led to increased burned area at a multi-decadal scale in Australia. This lack of trend is attributed to the high inter-annual variability and extremes of the Australian climate.

Here we use two remote sensing burned area products (AVHRR and MODIS) and agency data to show that burned area in Australian forests has increased over the past 32 years, with a regime shift after 2000, when megafire years (>1Mha burned) become a more common occurrence. The growth rate in burned area has been exponential during the cool months of the Austral autumn and winter.

The increased trend in forest burned area was tightly correlated with the increase in fire weather (FFDI), the increase risks associated with pyroconvection (C-Haines), and the increase in the frequency of dry lightning. Forest burned area was correlated with increased background biomass due to climate and atmospheric changes. This last result underscores the dominant role of climate and weather variables in driving the increase in burned area, all changing to various degrees due to anthropogenic climate change.

Consistent with the observed increased in forest burned area and fire weather projections, we suggest that fire is becoming an increasing negative impact on carbon storage, the hydrological cycle, and biodiversity.

TROPICAL CYCLONE FORMATION REGIONS IN CMIP5 MODELS: A GLOBAL PERFORMANCE ASSESSMENT AND PROJECTED CHANGES

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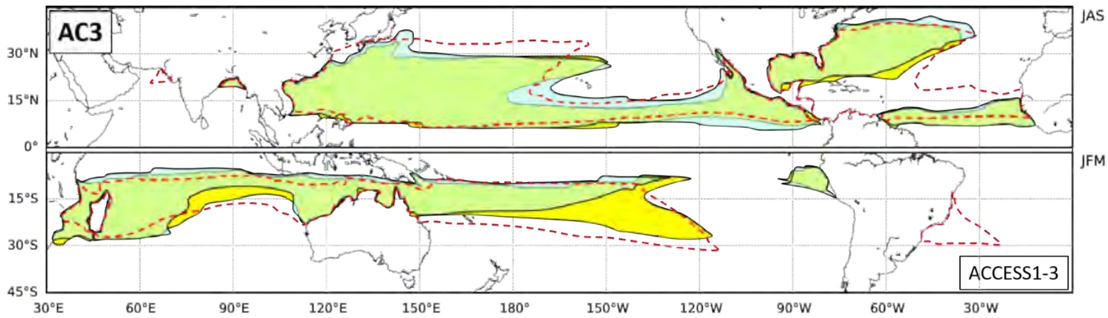
We analysed Tropical Cyclone (TC) formation regions in twelve CMIP5 models using a recently developed diagnostic (Tory et al. 2018) that provides a model-performance summary in a single image for the mid-summer TC season (Tory et al. 2020). Based on a subjective assessment of model performance of each TC basin throughout the globe, basins within each model were selected to investigate possible changes in TC formation regions in a warmer climate.

A slight poleward expansion in the western North Pacific and an expansion towards the Hawaiian Islands in the eastern North Pacific is plausible in the future, while a contraction in the TC formation regions in the eastern South Indian and western South Pacific basins would reduce the Australian region TC formation area. More than half the models were too active in the eastern South Pacific and South Atlantic basins. However, projections based on the remaining models suggest these basins will remain hostile for TC formation in the future. The figure that shows results common to many models including: i) poor performance in the North Atlantic Basin and ii), good performance in the Australian region. In the former, a large part of the most active region in the North Atlantic is diagnosed as unfavourable for TC formation (indicated by the absence of shading within and to the west of the Caribbean). The good performance in the Australian region provides some confidence in the projected contraction of the TC formation region evident there (yellow shading).



Projection map for the ACCESS1-3 model showing 31-year summer-season-average TC-formation regions for the historical (yellow shading) and rcp85 future (pale blue) scenarios (overlapping regions appear green). Red dashed lines indicate equivalent regions in ERA-Interim data.

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(NON-) INTERVENTION STRATEGIES FOR TROPICAL CYCLONE FORECASTING

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Forecasters have limited time to process the vast array of information during a TC shift especially with increased demands to focus on hazards and impacts. There is simply insufficient time to consider all the information at each step of the process. Priorities are set early on based upon the key decisions and issues on that particular shift. For example whether to put an area into watch or warning or making a track or intensity policy change as new information arrives. These priorities are associated with decisions being made by key customers such as setting community alerts and evacuations by emergency services.

Efforts to improve objective guidance leading to process efficiencies are therefore welcome. However, every forecaster has been burned at some stage by seeing a TC behave differently from objective guidance. Understanding the limitations of the methods is required to appropriately apply them with confidence and without undue intervention.

This study details identifies various objective inputs and describes the reliability and usefulness to both the analysis (position, intensity, wind structure etc.) and forecast (track, intensity, wind, rainfall and storm surge) stages. Opportunities for short-term gains in automation are proposed. A general comment is that many techniques are developed on just a few inputs and fail to consider other inputs. For example, SATCON intensity technique uses ADT and microwave intensity but not scatterometry or surface observations. Efficiencies in applying techniques also relate to how the information is made available. In general, techniques reside on unique websites and are not integrated with other viewing platforms, while some such as guidance on rapid intensification arrives via an email.

TROPICAL CYCLONE TRACK FORECASTING USING SUPER ENSEMBLES

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When forecasting tropical cyclone impacts, the cyclone's track is a significant factor because track uncertainty can be larger than the spatial extent of key hazards, such as the very destructive winds near the centre of the cyclone and the associated storm surge. Consequently, probabilistic track forecasting is an important component of impact forecasting for tropical cyclones.

Existing track forecast processes focus on minimizing the error of the "most likely track" by applying consensus methodology to the outputs of a range of Numerical Weather Prediction (NWP) models. The initial "range of likely tracks" (Forecast Confidence Cone) is based on the forecast track and accuracy statistics for the previous 5 years of forecasts. The forecaster can then subjectively adjust the Forecast Confidence Cone based on the spread of guidance, including ensemble guidance. The result is loosely calibrated, may subjectively vary from one forecast to the next, and does not fully utilize data from Ensemble Prediction Systems.

In this talk we describe work to derive the Forecast Cone from multiple Ensemble Prediction Systems (EPS). We refer to a combination of EPSs as a "super-ensemble" and demonstrate the benefits obtained from combining large numbers of track predictions generated from multiple EPS with significant independence in their error characteristics.

Using an Adaptive Bandwidth Kernel Density Estimate (AB-KDE) method we derive a Probability of Location (PoL) grid for a time step. From the PoL grid, we derive Forecast Confidence Areas (FCA) for a range of confidence levels. The 80% FCA is defined as the area in which the system centre is expected to fall on 80% of occasions. FCA's are calibrated using the last three years of global "best tracks". For a single confidence level, a series of FCA's are combined to give the Forecast Confidence Cone.

The new process results in greater automation and delivers a Forecast Cone based on dynamical ensemble guidance. The system also delivers richer, gridded data for our customers. For example, Strike Probability values (probability of system centre within a certain distance of a point) can be derived for a grid or a time series for a point. This work will also be used to generate graphical 7 Day Tropical Cyclone Outlooks for the Australian region.

ENSEMBLE MODELLING OF VOLCANIC ASH IN THE VAAC

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Volcanic ash in the atmosphere represents a significant hazard to aircraft and can incur significant costs to the aviation industry. To help mitigate these risks, the aviation industry funds a set of nine Volcanic Ash Advisory Centres; the Bureau operates one of these, nominally called VAAC Darwin. Improving the detection, monitoring, and forecasting of volcanic ash is a significant imperative of the aviation industry and its governing bodies. Each of these activities presents significant scientific challenges.

To improve volcanic ash forecasts to VAAC Darwin, the Dispersion Ensemble Prediction Scheme (DEPS) was implemented in May 2020. DEPS combines the NOAA HYSPLIT dispersion model with the Bureau's ACCESS Global Ensemble NWP model output to produce on-demand probabilistic forecasts of the spatial extent of volcanic clouds, typically out to 24 hours.

While DEPS represents a significant improvement to the forecast guidance provided to VAAC Darwin, large uncertainties remain and the ability to provide quantitative forecasts of ash concentration desired by industry by the mid-2020s remains limited at this time. Much of the uncertainty is associated with the specification of the volcanic 'source term', i.e. the characteristics of the volcanic eruption and associated volcanic clouds, with key issues being the spatiotemporal distribution of the eruptive plume, its mass eruption rate, and the size distribution of the particles.

Current research and development activities are focussed in several areas, centred around expanding the ensemble to account for uncertainties of the source term and making use of satellite-based quantitative retrievals of ash cloud properties (e.g. mass loading, height and particle size information). Combining this expanded ensemble with observations of the volcanic cloud position and with satellite retrievals results in improved forecasts when data assimilation techniques are used to filter out poorly performing ensemble members. Satellite-based retrievals of ash cloud properties in past eruptions have also been used to develop a new parameterization of the source term which has also been shown to improve the forecast in many cases when applied to new case studies, even without further input from real-time satellite retrievals. Quantitative retrievals can also be used in real time when available to further constrain the ensemble. Research to improve the representation of the particles within the dispersion model, including the size distribution and fall speed, is also underway.

The improvements to the DEPS model are expected to be operational by mid-2021.

THE IMPACT OF GLOBAL WARMING AND THE EL NIÑO-SOUTHERN OSCILLATION ON SEASONAL PRECIPITATION EXTREMES IN AUSTRALIA

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The El Niño-Southern Oscillation (ENSO) drives substantial variability in precipitation and drought risk over Australia. Understanding the combined effect of anthropogenic forcing and ENSO on Australian precipitation extremes over the coming century can assist adaptation efforts. Here we use 24 CMIP5 climate models to examine externally forced changes in the frequency of "droughts", when precipitation falls below the pre-industrial Decile 1 threshold. We focus on the southern hemisphere Winter–Spring season because precipitation during this period is important for agricultural production and recharging reservoirs in many parts of the country. The analysis in this study is based on two 90-year simulations (1900–1989 and 2010–2099) for Historical and RCP8.5 scenarios. We show that the frequency of droughts, including droughts occurring in consecutive Winter–Spring seasons, is projected to increase in the twenty-first century under the RCP8.5 scenario. Approximately 60% of years are projected to be drought years in Perth, 35% in Adelaide, 30% in Melbourne, and approximately 20–25% of years in Sydney, Canberra and Brisbane. However, this shifts in precipitation are accompanied by changes in the shape of the distributions whereby the high end of the distributions does not shift as much as other parts of the distribution and the wettest seasons become marginally wetter. This means that in most locations generally drier conditions are projected to be infrequently punctuated by seasons that are just as wet or wetter than the wettest years experienced during the twentieth century.

VICTORIAN RAINFALL PAST, PRESENT AND FUTURE

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Cool season (e.g. April to October) rainfall dominates the annual average over Victoria and is important for many crops and for replenishing reservoirs. Rainfall over Victoria during the cool season has been unusually low since the beginning of the Millennium Drought in 1997 (i.e., ~12% below relative to 1900-1959 average). Here we examine the extent to which this drying is driven by anthropogenic forcing, and the prospects for future rainfall, taking both external forcing and internal natural climate variability into account. We analyse simulations from 24 global climate models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) under preindustrial and historical forcing, as well as three scenarios for the 21st century: RCP2.6, RCP4.5 and RCP8.5, which vary markedly in the amount of greenhouse gas emitted over the coming century.

We show that while GHGs appear to have contributed to drying in the late 20th century, the effect in models is small and is offset by either volcanic or solar changes, internal variability, or from non-GHG anthropogenic forcing (e.g., sulfate aerosols). While the 1997-2018 average rainfall is below the preindustrial average in two-thirds or more of models, the magnitude of the externally-forced drying is very small. A majority of models indicate that both natural variability and climate change have contributed to the rainfall decline in the 1997 – 2018 period relative to 1900 - 1959, however the magnitude of external forcing contribution is relatively small. According to models, the externally-forced drying only becomes clear from 2010-2029, when the proportion of models exhibiting drying increases to over 90% under all three scenarios considered. While Victorian rainfall will continue to vary from year to year and decade to decade, models suggest that there is only a 12% chance that internal rainfall variability will completely offset the externally-forced drying averaged over 2018-2037, regardless of scenario. By the late 21st century the externally forced change under RCP8.5 is so large that drying – even after taking internal variability into account - appears inevitable.

However, confidence in our projections is lowered because models have difficulty in simulating the magnitude of the observed decline in rainfall. Some of this difficulty appears to arise because most models seem to underestimate multidecadal rainfall variability. Two other candidates are: the observed drying may have been primarily due to the occurrence of an extreme, internally-driven event; the models underestimate the magnitude of the externally-forced drying in recent decades; or some combination of the two. If externally-forced drying is underestimated because the response to greenhouse gases is underestimated, then the magnitude of projected changes might also be underestimated. We hope to investigate these issues using the next generation of – hopefully improved - climate models.

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INTERCOMPARISON OF RAINFALL EXTREMES IN GLOBAL IN SITU, SPACE-BASED AND REANALYSIS PRODUCTS

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As part of the International Precipitation Working Group (IPWG), GEWEX Data and Analysis Panel (GDAP), and World Climate Research Programme Grand Challenge on Weather and Climate Extremes (WCRP GC Extremes), a database has been developed which has enabled a comparison of multiple products on a daily 1° × 1° resolution. This database named Frequent Rainfall Observations on GridS (FROGS) is freely available from ftp://ftp.climserv.ipsl.polytechnique.fr/FROGs/ and contains data from a range of in situ, satellite, blended and reanalysis datasets. The aim of this study was to assess how the products compare using a standard suite of precipitation indices in order to determine whether these products can be used for long-term assessment of precipitation extremes (over land).

22 products from FROGS met the criteria for this analysis, namely that daily data were available over global land areas from 50°S to 50°N since at least 2001. From these daily gridded data, 10 annual indices that represent aspects of extreme precipitation frequency, duration and intensity were calculated.

Climatologies based on a common 13-year period (2001–2013) showed substantial differences between some products. Timeseries (which ranged from 13 years to 67 years) also highlighted some substantial differences between products. A coefficient of variation showed that the in situ products were most similar to each other while reanalysis products had the largest variations. Reanalyses however agreed better with in situ observations over extra-tropical land areas compared to the satellite clusters, although reanalysis products tended to fall into 'wet' and 'dry' camps overall. Some indices were more robust than others across products with daily precipitation intensity showing the least variation between products and days above 20 mm showing the largest variation. In general, the results of this study show that global space-based precipitation products have the potential for climate scale analyses of extremes. While we recommend caution for all products dependent on their intended application, this particularly applies to reanalyses which show the most divergence across results.

CLIMATE CHANGE AND EXTREME EVENTS: WHY EVERY YEAR MATTERS

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ABSTRACT NOT AVAILABLE

PROGRESS IN IMPACT-BASED FORECASTING ACROSS TIMESCALES: FROM IMPACT DATA TO RISK FORECASTS

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The scope of impact-based forecasting and warning has grown significantly over recent years and the value of cross-organisational and multi-disciplinary partnerships to achieve a better understanding and forecasting of risk is now well recognised by many meteorological services. This growth has highlighted the wide-ranging challenges associated with implementing impact-based forecasting approaches for operational use, including: access and quality of impact observations, integration approaches for hazard and consequence information, representation of dynamic vulnerability and exposure and the propagation of uncertainty throughout the impact modelling chain. This in turn provides a fantastic opportunity to undertake detailed underpinning science research that will support Impact-based forecasting and warning into the future. This presentation will highlight some of the progress made to enhance impact-based forecasting science and service delivery and will outline some of the current research being undertaken within the Met Office, including:

- Work to assess different styles of impact-based forecasting (e.g. hazard impact models, impact-based warning) and their value to different users.
- Review of vulnerability and exposure data, its use in impact modelling and the caveats and uncertainties that have implications for interpretability of risk.
- Use of social sensing and natural language processing to collect impact observations to enable evaluation of risk forecasts produced from hazard impact models.
- Research that looks at comparing hazard and impact model approaches at different forecast lead times and the implications this may have on usefulness and usability

THE ROLE OF DATA ASSIMILATION FOR CREATING DIGITAL TWINS OF THE EARTH SYSTEM

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Data assimilation is critical for a lot more than creating initial conditions for forecasts. It helps trace and characterize the key sources of model error at both weather and climate time scales, supports observation instrument inter-calibration and optimum observing system design even for future observing technologies, and is the basis of climate monitoring performed by reanalyses. Today's operational prediction systems run sophisticated data assimilation methodologies that evolved over decades and combine the best of variational and ensemble techniques to generate optimum estimates of the Earth-system state. At global scale, data assimilation represents an inversion problem with billions of degrees of freedom using hundreds of millions of observations per day. While limited-area systems rely to a large degree on the initial and boundary conditions provided by global systems, they add significant information through dedicated observations and run very high-resolution models as a separate, embedded inversion.

At present, two areas from which significant benefit is expected are convective-scale and coupled data assimilation, each being associated with their own, large challenges. As global models increasingly enter storm and convection resolving scales, they require initial conditions that contain information constrained by observations at such scales, which adds non-linearity and non-Gaussian statistical error properties. Coupling the atmosphere more tightly with ocean, sea ice, land surfaces and atmospheric composition requires data assimilation to also introduce coupling in the inversion, which adds complex cross-boundary error statistics and multi-scale systematic errors.

These scientific opportunities and challenges come with significant computing and data handling challenges. They affect very high-resolution and coupled modeling as much as very high-resolution data assimilation, with the additional challenge of ingesting large volumes of very diverse observations and dealing with a huge inversion problem for the latter. Further, the increasing need to fully integrate models and data from sectors affected by weather and climate in the workflow adds to the technical challenge but will greatly enhance the translation of Earth-system data into information with socio-economic relevance.

The concept of a Digital Twin, borrowed from industry, helps to bring these different aspects together and offers a platform whose benefit will go way beyond classical prediction science. The twin's software infrastructure would heavily rely on data assimilation methodologies but extend the optimization problem to socio-economic impact sectors and allow to address the extreme-scale computing and data handling problems. The twin's design requires Earth-system, impact and computational science to collaborate in new ways.

DATA ASSIMILATION FOR THE BUREAU'S OPERATIONAL SYSTEMS: AIMS AND CHALLENGES

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The Bureau of Meteorology currently uses the Unified Modelling System for atmospheric prediction. This has provided the Bureau with world class numerical weather prediction (NWP) and seasonal prediction systems. However, to meet the anticipated societal demands, against a background of technological and scientific developments, these numerical systems will require major changes. The broad outline of the Bureau's response to the evolving requirements are described in the Research and Development Plan for 2020-30. This presentation will outline the developments for the Bureau's data assimilation systems.

The key drivers for change are linked to both improving coupled modelling for both NWP and seasonal prediction, through coupled data assimilation, and the development of urban scale prediction systems.

Urban scale systems pose a particular challenge for both the observing and assimilation systems. Standard observations are too coarse to provide much information about the boundary layer in urban areas. However, there are many devices that operate in this environment that are weather sensitive. Harnessing these data sources to provide information to assimilation systems will require new approaches to observation processing. The nature of modelling at these scales also changes dramatically, and this also has direct consequences for the assimilation system. In a similar vein, the introduction of a coupled model breaks some of the fundamental assumptions of the variational atmospheric assimilation scheme.

These new systems are to be introduced at during a time of major change in High Performance Computing (HPC) technology which in turn is forcing a major overhaul of the modelling software to the Next Generation Modelling System. This transition provides the opportunity to explore a variety of options regarding both the variational assimilation and the observations used by the assimilation.

STATUS AND RECENT ADVANCES IN ASSIMILATION OF SATELLITE DATA IN BUREAU WEATHER PREDICTION MODELS

Fiona Smith, Chris Tingwell, Yi Xiao, Susan Rennie, John Le Marshall, Jin Lee, Robert Pipunic, Peter Steinle, David Howard, Leon Majewski, Alessandra Monerris-Belda, Chris Bridge

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This talk will summarize the importance of satellite data within the global observing system that supports the Bureau's numerical weather prediction (NWP) models. In global models, satellite observations represent around 95% of all observations assimilated, providing global coverage of measurements sensitive to the atmospheric temperature, humidity, and wind. These observations are particularly important for weather forecasting in the Southern Hemisphere, where there are fewer conventional upper air observations available.

The Bureau's global NWP model, ACCESS-G3, has been operational since July 2019. This configuration included satellite observation sources new to the Bureau. ACCESS-G3 was upgraded in June 2020 with a further enhancement to the data assimilation, including further additional satellite observations, improving the reliability of the observing system and providing good forecast impact.

The new city-scale models, ACCESS-C3, have been operational since August 2020 and also benefit from assimilation of satellite observations, in particular those received by the Bureau's satellite network, which provides rapid access to polar orbiter observations and atmospheric motion vector winds.

The status of the assimilation systems for ACCESS-G3 and ACCESS-C3 will be described. The Bureau's Research and Development plan has a strong reliance on increasing our usage of satellite observations, and the short to medium term goals to support this will be described.

DEVELOPMENT OF AOM2/ENKF OCEAN FORECASTING SYSTEM

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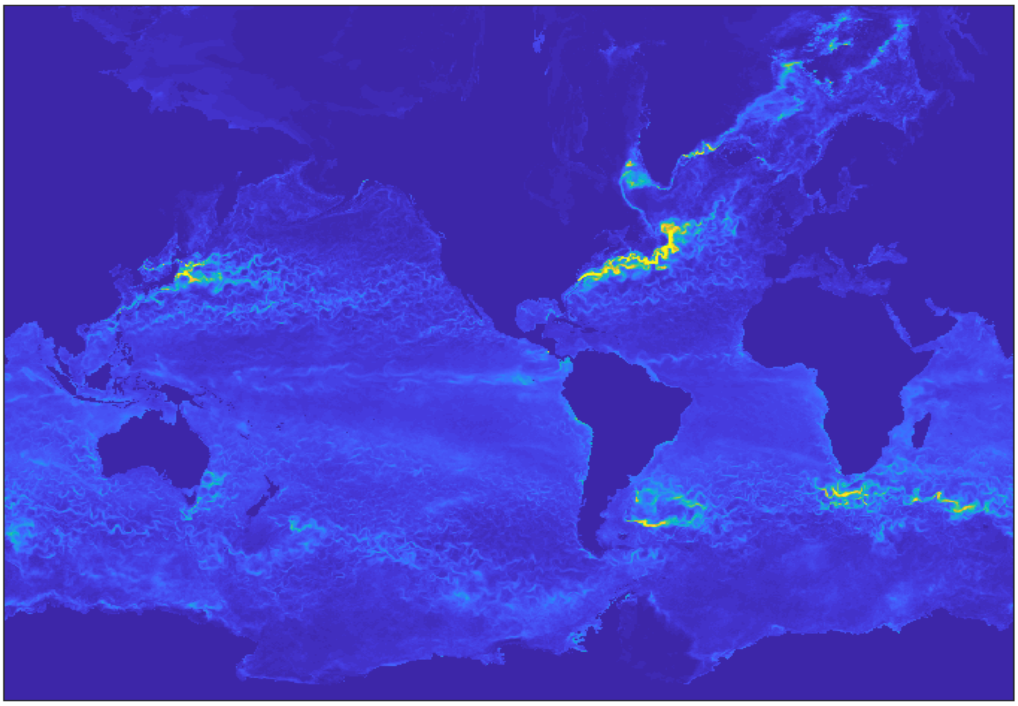
Version 4 of the OceanMAPS ocean forecasting system is being developed by the Bureau and represents a significant advancement. Version 3.3 of the OFAM3 model is being replaced by the coupled ocean-sea ice model AOM2-01 (ACCESS Ocean Model v2 0.1°) developed by the COSIMA project (Kiss et al. 2020), and the EnOI data assimilation system is being replaced by the EnKF system (Sakov 2014). In this talk we discuss the basic vision behind the system design, describe the current state of the development, and present first results from the new system.



An example of the SST ensemble spread from the AOM2/EnKF system

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THE JOINT EFFORT FOR DATA ASSIMILATION INTEGRATION (JEDI)

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ABSTRACT NOT AVAILABLE

RADAR RAINFALL, WIND, AND HAIL ANALYSIS AND NOWCASTING DEVELOPMENTS AT BOM

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Introduction

The Bureau of Meteorology's (BoM) Public Services Transformation (PST) program has identified the need to uplift the BoM rainfall, wind and hail analysis and nowcasting (i.e., very short-term forecasts, up to about 1 hour) services, leveraging from new capabilities of the radar network. These new services will help BoM forecasters issue more accurate and rapidly updating warnings and alerts about current or imminent severe weather to the general public and customers. It will also help emergency services deploy resources for the return to service of critical infrastructure impacted by severe weather. In this talk, we present the current status of development of this new generation of analysis and nowcasting services under development, which should become operational by 2022. These nowcasting services are quickly described below and will be discussed in more detail during the presentation.

Rainfall analysis and nowcasting

Three main pieces of work are ongoing to improve the rainfall analysis and nowcasting service: (i) further improving the *Rainfields* rainfall accumulation product by developing tailored relationships between rainfall rate and radar reflectivity that account for the regional and seasonal variability of Australian rainfall; (ii) leveraging from the new dual-polarization capability of the operational radar network by developing a dual-polarization rainfall retrieval algorithm based on the pioneering work of the US National Severe Storms Laboratory; (iii) recoding and improving the scientific core of the operational Bureau *STEPS* rainfall nowcasting technique (radar-only version named *STEPS-ADV*, and blended radar – high-resolution NWP ACCESS-C version named *STEPS-NWP*). More information can be found at: http://www.bom.gov.au/research/publications/researchreports/BRR-045.pdf.

3D wind analysis and nowcasting

In-house research-grade Single-Doppler and multi-Doppler 3D wind retrieval techniques are being transitioned to operations to provide convective-scale diagnostics such as wind shear, mesocyclone detection, vorticity, updraft helicity, and vertical velocity diagnostics in real-time. Nowcasting techniques will also be explored in this project to provide up to 1h nowcasts of such diagnostics and help forecasters issue severe weather warnings. Here we show a blended single-Doppler / multi-Doppler wind retrieval for the 14/10/2014 East Coast Low.

Hail analysis and nowcasting

In collaboration with the University of Queensland, an innovative dual-polarization multi-Doppler hail nowcasting technique named HailTrack, has been developed and validated using gridded insurance claims data. This technique uses 3D trajectories to predict the size and location of hail at ground. It is being currently extended to single-Doppler and single-polarization in order to produce nowcasts from all Doppler radars of the network

VARIABILITY, CLOUDS AND EXTREME RAIN IN THE MARITIME CONTINENT

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On a local scale, convection, clouds and heavy rainfall over land areas of the Maritime Continent (MC) are dominated by mesoscale processes that show complex relationships to the expected responses of intra-seasonal and interannual variability. Examination of local processes reveals interactions across almost all atmospheric scales, from microscale surface fluxes to diurnal, synoptic, intra-seasonal and interannual scales. In this work, we present evidence of scale interaction on multiple scales over islands of the MC.

Previous work has demonstrated clear evidence of inter-scale interactions in the MC, including modulation of the diurnal cycle and rainfall extremes by intraseasonal variability (eg. Peatman et al. 2014, Vincent & Lane 2017, Lestari et al. 2019), modulation of intraseasonal variability by the topographic and coastal effects of the MC (e.g. Baranowski et al 2016.), or interaction between ENSO and the MJO (eg. Wei and Ren 2019). Here we present evidence of variability and its scale interactions from a range of high-resolution datasets, including Himawari-8 satellite observations, Asia-flux sites in the Maritime Continent, the Jakarta CPOL radar, ERA-5, station data and the ISCCP database.

We show evidence of the rainfall response to the MJO varying strongly with topography and distance from the coast, both in terms of the phase of maximum rainfall and the amplitude of the response. We demonstrate the competing roles of local surface forcing and background column moisture in modulating the afternoon and evening diurnal rainfall peak over land. We also demonstrate variability associated with ENSO, intraseasonal variability and a cold-surge event, and their interactions with the local topography of Java and Sumatra.

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CONVENTIONAL AND EXPERIMENTAL ANALYSIS OF THE 19 JAN 2020 MELBOURNE HAILSTORM- WHAT CAN WE LEARN FOR FUTURE NOWCASTING SERVICES?

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19 January 2020 Hailstorm

On Sunday the 19th of January 2020 a severe hailstorm impacted areas of northeastern, eastern and south eastern Melbourne, producing large (2+ cm) to giant (5+ cm) hailstones. This event was part of a larger outbreak of severe thunderstorms across Brisbane, Sydney, Canberra and Melbourne, resulting in $1.8B in insured motor and property losses (reported by PERILS, July 2020). The passage of Melbourne hailstorm through a densely populated urban area provided a number of unique observational opportunities and applications that will be explored by this presentation.

Observations

For the Melbourne region, the 19 January hailstorm event was observed by the Laverton polarimetric Doppler weather radar, which can be utilized to retrieve both conventional and modern-polarimetric hail size estimates. In tandem with the Broadmeadows Doppler radar, dual-Doppler coverage of the event also allows the 3D wind field to be retrieved, further extending capacity for hail analysis by allowing for the simulation of hail trajectories and more accurate hail size mapping (HailTrack; Brook et al. 2020). In addition to these operational observations, experimental observations were also collected. These include aerial surveys of hail geometry and concentration, hail-damaged car bonnets for assessing hail concentration and preserved hailstones to laboratory assessment of 3D-geometery and growth modes.

Future Hail Nowcasting

Current hail retrieval techniques applying sizing algorithm which can be correcting further using melting and advection adjustments (Alain Protat et al., this session). A critical step missing from this process is estimating the potential for further hail growth, which has the potential to further increase the size accuracy and lead-time. Ongoing research using the unique set of conventional and experimental observations collected during the Melbourne hailstorm to better understand the radar signatures associated with hail growth.

HEAT ON HUMAN HEALTH AND WORK PRODUCTIVITY: HEAT STRAIN OVER HEAT STRESS

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Occupational heat on health, work productivity and safety have attracted new attention due to climate change and projections of heat stress in most parts of the world. While important, heat stress is not the sole contributor to the resultant heat load induced on the worker (heat strain). In addition to defining heat stress and heat strain, I will provide an overview of the physiological basis for occupational heat and related effects that may develop. While outdoor jobs in the sun create particular risks, many workers in factories in tropical areas are also exposed to excessive heat because cooling systems may not always be available or encouraged. Excessive heat exposure in workplaces can cause accidents (compromising safety), heat exhaustion (decreasing work productivity) and heat stroke (degrading health) unless the worker is able to take action to reduce heat strain, such as by reducing work intensity or taking frequent breaks and using effective heat mitigation strategies (Figure 1). These protective actions should reduce health risk and enhance work productivity. The workforce in many countries is also ageing, and older people are more vulnerable to heat than younger people. Policies related to the reduction of occupational heat strain can be implemented to preserve the wellbeing of labourers and work productivity with climate change.

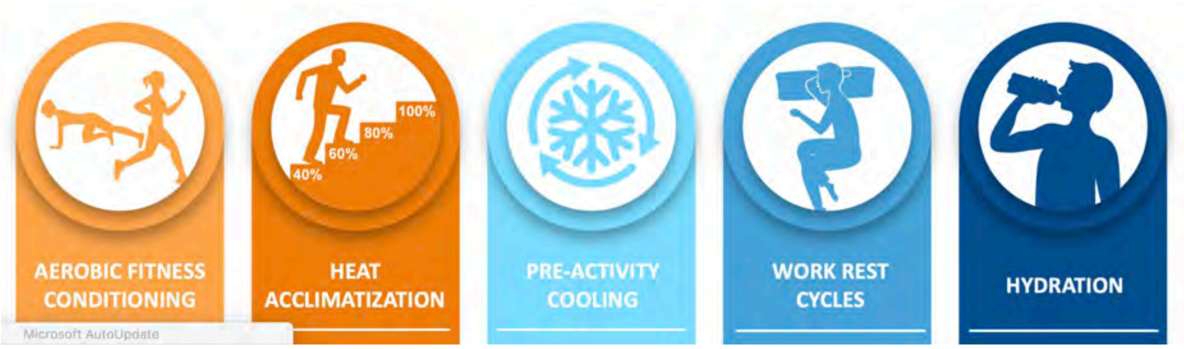

Figure 1. Heat mitigation strategies to safeguard our well-being, health and productivity.

THE SURFACE WATER OCEAN TOPOGRAPHY (SWOT) MISSION: OPPORTUNITIES AND CHALLENGES

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Australia's Blue Economy, defined as economic activity related to the ocean, seas, and coasts, supports an estimated 393,000 FTE jobs nationally (AIMS, 2018). By 2025, marine industries such as defence, offshore oil and gas, fisheries and shipping are forecast to grow to more than $100B per year (MNSP, 2015). These industries, and the jobs they support, rely critically upon satellite geospatial data about the dynamic ocean environment to guide decision-making and operational safety.

In the coming decade, new satellite missions will map Earth's surface water and sea level (ocean topography) at a resolution that has not been possible before. These observations will provide critical information that is needed to assess water resources on land, track regional sea level changes, monitor coastal processes, and observe small-scale ocean currents and eddies. The first of these satellites, the NASA/CNES Surface Water Ocean Topography (SWOT) mission, is scheduled for launch in early 2022 (Morrow et al., 2019).

In this talk, I will present an overview of the SWOT mission objectives and discuss future challenges and opportunities for operational oceanography in the region. I will also outline the goals and activities of the Australian Surface Water and Ocean Topography Working Group (www.auswot.org), a consortium of researchers and stakeholders in academia, government, and industry working to develop Australia's capability in the field of wide-swath altimetry. Finally, I will discuss opportunities for Australian researchers and government agencies to carry out synergistic in-situ activities that will support the SWOT mission and maximise the benefit to Australia's Blue Economy (D'Ovido et al., 2019).

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ENHANCING AUSTRALIA'S NETWORK OF COASTAL WAVE OBSERVATIONS USING LOW COST WAVE BUOYS

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ABSTRACT NOT AVAILABLE

HIMAWARI FOR DETECTING AND PREDICTING SEVERE WEATHER

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OPPORTUNITIES FROM NON-TRADITIONAL OBSERVATIONS

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The Bureau has recently begun a major plan that aims to guide the future composition of its observations network over the next 20 years. While the world itself is changing, with trends in severe weather and climate events on the rise, the way in which observations are taken, managed and used is also changing as a rapidly increasing array of observation systems, data types and platforms, now being created and deployed by others, provide a myriad of new opportunities for the Bureau. Some are very familiar, such as third party mesonets and private weather stations, all of which are arguably under-used by the Bureau. Less familiar are the potential opportunities from non-traditional observations, such as from motor vehicle, mobile phone and smart, lower cost IoT sensors, cellular communication networks, social weather platforms (such as photos and reports of weather impacts) and networks of new data types (new to the Bureau), such as solar, UV, and air quality. We are also watching with great interest the sensing developments from cube-satellite constellations and many other technologies. These non-traditional data have the great potential to strengthen the critically needed forecasts and warnings reaching Australians and to enhance our broader understanding of the atmosphere and oceans.

This future builds on the concept of a 'network of networks' with the Bureau forming new partnerships and collaborations to gain access to these new data. This has already begun with the Bureau and CSIRO collaborating on Trusted Private Automatic Weather Stations, a project to quality control third party weather station data; WeathExApp, a collaboration with Monash University and others to support verification of warnings and improve nowcasting of severe thunderstorms; and WOW (Weather Observations Website) a collaboration with the UK Met Office to provide a cloud platform to effectively share, on a global scale, private weather station data. We are also beginning to discuss and collaborate with other NMHS', universities and companies at the cutting edge. This is just the beginning.

The world will look very different in 20 years' time, and to ensure that our observation network continues to meet the needs of customers in 2040, we need to begin planning now. For example, motor vehicles are likely to be autonomous. Our observations and analyses on the environment and road state could enhance the safety and efficiency of traffic in different conditions. Drones will also likely be more widely used along with the growth of smart, connected IoT sensors, and cloud and edge computing which is growing in response to the demand for remote sensing equipment that is compatible, easily integrated, cloud-ready and secure. In a changing climate, our customers will need to be informed by real-time, localised environmental observations and in our most populous urban environments, a local understanding of the weather and impacts to health and safety will certainly become increasingly important. Finally, while Australia's energy systems transform, we will see more demand for real-time forecasting capabilities, and continuous monitoring.

In response to these challenges for the observations network we have begun to collate some exciting ideas for the future use of non-traditional observations. I will describe a few. Our next step is to build on these ideas, assess their benefit, and extract value to tailor services that harness scientific advances for existing and expected customer's benefit. It will change the way the Bureau does its observations business.

THE ROLE OF AUSTRALIA'S INTEGRATED MARINE OBSERVING SYSTEM IN UNDERSTANDING OUR FUTURE OCEANS

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Australia's Integrated Marine Observing System (IMOS) is a national research infrastructure, supported by the National Collaborative Research Infrastructure Strategy (NCRIS). Since 2006 IMOS has routinely operated a wide range of observing equipment throughout Australia's coastal and open oceans, making all of its data openly accessible via the Australian Ocean Data Network. IMOS data holdings include physical, biological, biogeochemical and atmospheric variables accessible to the marine and climate science community, industry, stakeholders, end-users and international collaborators. IMOS data are fundamental to many marine, climate and weather models to better understand ocean processes and ecosystems as well as the broader environment, including climate change. For example, IMOS provides data to better understand marine heatwave events and their implications on sensitive environments such as coral reefs. The existence of a sustained observing system provides a unique opportunity to understand the implications of these extreme and episodic events. In addition, the breadth of the IMOS program allows the capacity for data integration to improve our understanding of marine systems and explore solutions to complex problems.

As IMOS looks to the future and works to ensure the observations we collect are relevant to research, modelling, forecasting and other uses, we are working to integrate data streams to increase use of the data. Integrated data products allow multiple users and non-specialists to access, apply and interpret IMOS observations to help address issues of national and international significance. In addition to data integration, IMOS is currently exploring new elements of observing and the scope and scale of the IMOS program over the next 5-10 years. By examining the potential of IMOS observations to create societal benefit for Australians we hope to ensure continued and increased benefit from the IMOS program. The data we collect today is critical to defining and measuring change in our ocean ecosystems and weather now and into the future.

CLOUD HPC

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ABSTRACT NOT AVAILABLE

SCALING RESEARCH ON THE CLOUD WITH AWS HPC AND DATA SHARING

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ABSTRACT NOT AVAILABLE

ACCESS-NRI: WHAT IT IS, WHAT WAS PROPOSED, AND WHY

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Background

The Australian Government responded in 2018 to the 2016 National Research Infrastructure Roadmap by establishing scoping studies for eight additions to our National Research Infrastructure (NRI). First on the list was enhancing the Australian Community Climate and Earth-System Simulator (ACCESS) - a large computer modelling system for research with atmospheric, ocean, sea-ice, and land surface models coupled to a range of chemical and biological models. It models the evolution of climate, weather and the earth's environment at all timescales up to millennial. The ACCESS-NRI Scoping Study commenced in August 2018, submitting its report with a proposed facility design at the end of July 2019. ACCESS-NRI was supported in the 2020 budget

The Two Challenges

First, ACCESS will fall behind without professional software engineering support from a facility such as the ACCESS-NRI. The ACCESS system's complexity and size have grown to the point where its three and a half million lines of computer code cannot continue to be developed, curated, validated and maintained by a limited number of individual scientists. Second, in relatively few years high performance computing architecture will change to one or more new architectures under the rubric "exascale". The current ACCESS code will not run on the emerging architectures, a problem faced by all international modelling groups.

The Response: ACCESS-NRI

Following consultation with agency and university researchers, ACCESS users, and software engineers the Scoping Study developed the design for ACCESS-NRI. The resultant design is for a software engineering facility configured into teams supporting each of the model components, the coupling of those components, implementation of international software engineering standards, curation, validation, version and release control, and a dedicated user support system. That system will enable a far broader research community to use ACCESS.

Key Points

- ACCESS includes several million lines of code, running on high performance computers combining atmospheric, ocean, sea-ice, and land surface models
- ACCESS has been built by CSIRO, the Bureau of Meteorology and University teams
- The transition to exascale will leave ACCESS "stranded", unless re-engineered
- The ACCESS-NRI will provide a facility to ensure ACCESS can use new computing architectures and maintain the only world-class research system in the SH
- ACCESS-NRI is supported by five Australian Universities, CSIRO and Bureau of Meteorology. Two more universities offered additional support, with thirteen universities expressing interest based on increased usability from a new, fully supported user system
- The ACCESS-NRI facility will be hosted by the ANU, close to the NCI
- The ACCESS NRI will provide the research tools and research collaboration needed to address national challenges in weather and climate risk and environmental change
- The ACCESS-NRI will deliver improved capacity to warn business, government and the public about these risks, and to mitigate the risks with scientifically informed strategies
- ACCESS-NRI will place us at the forefront of international weather and climate modelling, and provide national leadership in the technological and software innovations required to move many areas of computing and data intensive research to exascale.

TO BE CONFIRMED

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ABSTRACT NOT AVAILABLE

INTEGRATED ENVIRONMENTAL PREDICTION: ECMWF PROGRESS AND PLANS

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ECMWF takes an earth-system approach to analysis, prediction and environmental monitoring, both in order to extend to range of outputs provided (e.g. through Copernicus services for composition, flood and fire) and because such an approach can lead to improvements in traditional ensemble-based forecasts for timescales from medium-range to seasonal. This talk will highlight a number of key developments made to the NWP system in recent years. These include the introduction of a coupled ocean from day 0, significant developments to the data assimilation system (e.g. continuous DA; weak constraint 4D-Var) and extensive efforts to extract still more value from an ever-increasing range of atmospheric observations (e.g. Aeolus wind profiles). Together these developments have continued to deliver the significant advances in prediction accuracy to which we have become accustomed.

Looking ahead, further improvements to the representation of individual earth-system components will remain crucial. In addition however, we also envisage further integration across earth-system components. In part this will be in the model (e.g. extending the complexity of aerosol representation in NWP in order to capture feedbacks on the meteorology; better snow modelling to improve land-atmosphere interactions). However, it is important to also stress the importance of an earth-system approach in the data assimilation and use of observations – at present much potentially valuable data is under-utilized (e.g. satellite data which is affected by both the atmosphere and the surface), and further coupling, both through the observation operator and directly through the DA system offers significant promise. Plans in this direction will be described.

TOWARDS IMPROVING WEATHER PREDICTION THROUGH HIGH RESOLUTION MODELLING SYSTEMS

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Advances in high-performance computing have allowed national weather services to run operational weather models with horizontal grid lengths of O(1 km). High-resolution models have the advantage of being able to resolve important mesoscale flows and represent storms and precipitation explicitly. By allowing an explicit representation of these processes, high-resolution model forecasts provide unparalleled guidance for severe weather warnings of heavy rainfall, wind gusts and hail.

While the high-resolution models present many advantages, the smaller grid sizes create a challenge in terms of predictability. Small-scale forecast errors grow quickly and because convective processes are nonlinear, they are strongly affected by uncertainties. Increasing supercomputer capability enables the production of an ensemble of high-resolution forecasts. Ensembles help quantify forecast uncertainty and provide the degree of confidence that users should have in a particular forecast.

This presentation will illustrate the realism of weather phenomena in high-resolution models and the benefits of using high-resolution ensembles to understand forecast uncertainty. The advantages and challenges of sub-km scale modelling will be discussed, including the explicit representation of tornadoes in 100m grid length ensemble simulations.

A CASE STUDY OF A TROPICAL LOW OVER NORTHERN AUSTRALIA USING HIGH RESOLUTION MODEL

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We examine in some detail a low that intensified over land near the northern coast of Western Australia in January 2015. The study is based on European Centre for Medium Range Weather Forecasts (ECMWF) analyses as well as two cloud-permitting, 6-day, limited area, forecasts using the UK Met. Office Unified Model (UM) with 4 km grid spacing. In one of the UM forecasts, the latent heat fluxes were suppressed over the land so as to assess the importance of soil moisture on the intensification of the low. We show that the UM forecasts perform well using the ECMWF analyses as "truth", suggesting that the forecasts can be used to learn about the details of storm behaviour. Analyses of the forecasts support the results of previous studies showing that the intensification of the low over land can be interpreted in terms of the rotating-convection paradigm intensification articulated in recent studies. The forecasts indicate also that high soil moisture or special soil types are not essential to vortex intensification over land, at least in a monsoonal environment.

USING HIGH RESOLUTION NWP IN FORECASTING IMPACTS OF SEVERE WEATHER

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The latest version of the Bureau's convection-allowing ACCESS City model was operationally commissioned on 10th August 2020 featuring a number of significant advances and improvements, including the output of 'storm attributes' - surrogate diagnostics of severe thunderstorm hazards from explicitly simulated thunderstorms within the model. Presenting a new paradigm with respect to NWP interrogation and interpretation for Bureau severe weather meteorologists, the mesoscale features of simulated thunderstorms are exploited to provide meaningful insight into, and assist in the communication of, not only where thunderstorms may occur, but what thunderstorms may do.

An introduction to the storm attribute fields and visualisation strategies implemented by the Bureau to support the future high standard of severe weather forecasting are presented. These range from summary fields that provide efficient identification of severe thunderstorm risk areas, swathes and intensity, to high spatial and temporal resolution fields that resemble realistic appearing convective structures.

Post-processing and visualisation strategies for the new ACCESS City Ensemble system that provides a range of possible thunderstorm solutions are presented. These can be used to quickly assess the most likely outcome, quantify uncertainty and summarise information pertaining to convective mode, intensity, location and timing of thunderstorms.

Examples from recent severe thunderstorm events are presented to demonstrate the benefits of these new products to operational meteorology. A brief overview of the training strategy that supplements the implementation is also provided.

GLOBAL FIRE WEATHER TRENDS

Mike Flannigan[1], John Abatzoglou[2], Dante Acuna[1], Sean Coogan[1] and Piyush Jain[3]

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Globally, the area burned from vegetation fires is around 400 million hectares (approximately the size of India) a year. There are three ingredients necessary for a fire to occur, fuel, ignition and conducive weather. Temperatures have been rising in recent decades and this will influence the fire weather. We use ERA5 data to calculate components of the Canadian Fire Weather Index (FWI) System. This FWI System is weather based and represents how fast a fire might spread (Initial Spread Index), how much fuel might burn (Build Up Index) and how intense the fire will be (Fire Weather Index). Temperature, relative humidity, wind speed and 24-hour precipitation are the meteorological inputs for the FWI System. For the period 1979-2019, we examined the trends in the mean and extremes of the FWI System as well as the vapour pressure deficit (VPD) during the fire season. VPD was included as VPD has been shown to be related to fire activity.

Results globally show a wide-spread increase in FWI System components as well as VPD. Western North America, the Mediterranean eastern Australia as well as parts of South America and Africa. Decreasing trends did appear for some variables in India and the northern plains in North America. These results explain, in part, the recent increases in fire activity in many regions of the world. These increases are consistent with many of the climate change projections of future global fire activity.

INDO-PACIFIC PEG

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ABSTRACT NOT AVAILABLE

THE IMPORTANCE OF MODEL MEAN STATE BIASES - A PERSPECTIVE ON TROPICAL TELECONNECTIONS

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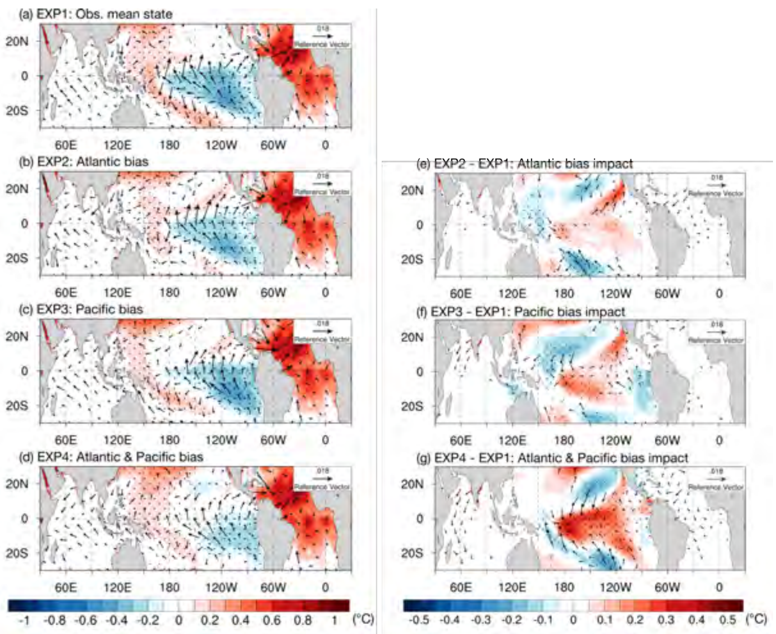
Global surface temperature is the most broadly used indictor for the mean climate state and climate change, and one of the primary criteria for the evaluation of climate models in the Intergovernmental Panel on Climate Change (IPCC). Despite the improvement of the simulated surface temperature in many aspects through the generations of coupled climate model development, there are still a large range of modeled surface temperature biases in some particular regions (e.g. the equatorial Pacific and Atlantic SST biases, the land surface temperature biases in high topography), creating a source of uncertainty for the future climate projections.

Here we address the important role of model background SST biases in representing the Atlantic-Pacific teleconnection, while noting the failure of climate models to reproduce the Pacific cooling trend in recent decades may partly be due to the underrepresentation of trans-basin teleconnections. Our targeted model simulation results suggest the magnitude of Pacific cooling response to a fixed Atlantic forcing is significantly reduced when background SSTs in either the Pacific or Atlantic region are nudged towards the biased CMIP5-like mean state, relative to the observed climatology simulation. Thus, future efforts aim at reducing the model mean state biases may significantly help to improve simulation skills of the trans-basin teleconnections.



Sea surface temperature and surface wind stress response to the Atlantic warming forcing under different background SSTs mean state.

FORECASTING NORTHERN AUSTRALIAN WET SEASON BURSTS IN ACCESS-S1

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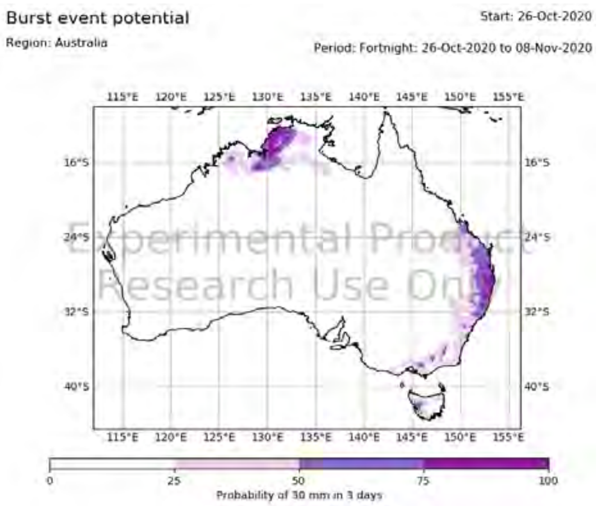
Wet season bursts are relatively short-lived rainfall events that typically occur over a period of a few days to a week. Here we define a burst as when at least 30 mm of accumulated rainfall occurs over 3 consecutive days, similar to the "green break" rule used by northern Queensland graziers to mark the first decent rainfall of the wet season (Oct-Apr). Coinciding with a prototype burst product release (see figure below), we evaluate wet season rainfall bursts for northern Australia's tropical regions over the period 1990-2012 in observations and calibrated multi-week hindcasts from the Bureau of Meteorology's seasonal prediction system, ACCESS-S1 (Australian Community Climate and Earth-System Simulator, Seasonal version 1). There is a tendency for ACCESS-S1 to overestimate the total number of wet season burst days (frequency) for tropical regions north of 20°S, as well as positive biases in the proportion of wet season rainfall from bursts.

In terms of hindcast skill, the temporal correlation of burst frequency is significant out to a lead time of about three weeks, with better skill over the tropical northwest compared to the northeast. By simplifying our framework to focus on the prediction of any burst event in the forecast period, we find that, based on a brier skill score, ACCESS-S1 shows good skill out to week 4 over the Top End and Cape York. We further test whether hindcast burst skill is enhanced when the hindcast ensemble mean predicts strong Madden-Julian Oscillation (MJO) amplitudes. Initial results suggest there is improved skill in burst event prediction out to four weeks over the Top End alongside a prediction of strong MJO activity, however for the far northeast, there is better burst forecast skill when weak MJO amplitudes are predicted. The ability of ACCESS-S1 to skillfully forecast bursts out to 2-3 weeks would be of significant interest to northern Australia livestock producers, where important weekly management decisions on cattle stations very much depend on accurate multi-week rainfall forecasts.



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An example of a prototype burst product, showing the probability of a 30 mm in 3-day burst event occurring in the first fortnight (26-Oct to 8-Nov 2020), based on 99 ACCESS-S1 forecasts initialised on the 26-Oct 2020.

BALANCING THE VALUE OF INTEGRATED DATA AND PRIVACY IN TODAY'S DATA ECONOMY

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Data is quite literally everywhere. It is the raw material that underpins the value of the global economy and determines economic, social, and environmental frameworks and policies. Data drives productivity, efficiency, innovation, and growth in all areas of society, but creating an optimal balance between the "protection of individual privacy" and the "beneficial uses of data" continues to be debated across varied forums. Technological advances in big data, e.g., data mining, predictive analysis. artificial intelligence, computational power and storage, and Cloud capability continue to exponentially expand the scope of information available to governments, businesses, and individuals. Increased connectivity for people and their devices due to improved digital networks has revolutionised our ability to not only generate and share data, but also to collect and provide access to it. Data custodians such as the Australian Bureau of Statistics (ABS) face increasing pressure to allow access to more integrated data assets, while at the same time being expected to ensure the confidentiality of individuals and businesses providing data.

The increased integration of large data sets for analysis and research purposes has legitimate privacy implications and creates on-going challenges for data security and privacy protection. Despite the routine use of confidentiality processes and strict governance protocols by government data custodians such as the ABS, some concern remains about intrusion and loss of control of personal data, for example, health, education, income, migrant status, and location. Legislation to both protect privacy and data collection is premised on an individual's control over their data and how it is shared. So how do we balance the needs of upholding societal values and data protection principles? This presentation will discuss 1) the advances in data access, including the ABS DataLab; 2) the creation, use, management and value of integrated data assets, such as the Multi-Agency Data Integration Project (MADIP) and the Business Longitudinal Analysis Data Environment (BLADE); and 3) the reforms in data sharing and protection legislation.

CITY ENSEMBLE: UNCERTAINTY INFORMATION IN HIGH RESOLUTION NWP

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The Australian Bureau of Meteorology (Bureau) is currently rolling out its first convective scale ensemble forecasting system called the Australian Parallel Suite 3 (APS3) Australian Community Climate and Earth-System Simulator (ACCESS) City Ensemble (ACCESS-CE3 or CE3). ACCESS-CE3 is a 12 member, 2.2 km resolution ensemble running 4 cycles per day to T+39 hours. Release 1, in November 2020, delivers three East Coast domains: Brisbane, Sydney and VicTas. In early 2021, Release 2 will deliver four additional domains: Adelaide, Darwin, Perth and North Queensland.

The base initial conditions for CE3 are provided by C3, a 1.5 km resolution system with a 4D-Var Data Assimilation (DA) cycle. Large scale perturbations and lateral boundary conditions are provided by the Global Ensemble (GE3). The large scale perturbations, the residuals from the global ensemble members and control member, are integrated with the base initial conditions to create unique initial conditions for each CE3 ensemble member. The majority of the spread in the ensemble is due to the initial condition perturbations and boundary conditions. The remaining spread is generated by the stochastic physics package known as the Random Parameter (RP) scheme.

The RP scheme aims to incorporate uncertainty in the values of parameters in the model’s physical parameterisation schemes. It varies the values of ten parameters within the model which cover the following physical processes: mixing in the boundary layer, cloud formation, cloud-top diffusion, precipitation and droplet settling near the surface (McCabe et al., 2016). The RP scheme’s contribution to the overall spread of the ensemble is an order of magnitude less than the contribution from the large scale perturbations and boundary conditions, yet it is still important as it helps to address under-dispersiveness in the ensemble. ACCESS-CE provides a range of physically realistic future states of the atmosphere, providing users uncertainty information. This is particularly useful for meteorological phenomena that are locally driven such as convective events.

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IMPROVER POST-PROCESSING OF NWP ENSEMBLES

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The Bureau of Meteorology currently operationally uses 'Gridded OCF' post-processed guidance as a key input to produce public weather forecasts. Gridded OCF uses multiple deterministic numerical weather prediction (NWP) model inputs, and recently some ensemble inputs, to produce deterministic forecast outputs, except for precipitation which has probabilistic outputs. However, technical limitations such as ability to handle large numbers of ensemble members are being encountered with Gridded OCF. For similar reasons, around 2016, the UK Met Office embarked on development of a long term post-processing strategy, utilising a new system called IMPROVER. IMPROVER focuses on gridded and probabilistic processing, with site and deterministic forecasts derived from probabilistic grids. The Bureau of Meteorology and the UK Met Office have agreed to collaborate on development of the IMPROVER system, with the intention that IMPROVER replaces Gridded OCF in operations at the Bureau.

The Bureau implementation of IMPROVER for the Australian domain will share the same code as the Met Office implementation, but use a significantly different configuration. Configuration differences arise from the six input ACCESS-C/CE NWP domains which partially cover the Australian forecast region compared to the single UKV and MOGREPS-UK domain, the use of a wider variety of global models in Australia compared to the UK and the use of a separate analysis system (National Analysis System) in Australia rather than UKV analyses.

Processing high resolution convection allowing ensembles (ACCESS-CE) raises several challenges for post-processing systems. These challenges include managing detail in each ensemble member that is overly specific for some purposes, low numbers of ensemble members resulting in a non-smooth probability density function, rapid updates where data from multiple NWP models arrives continuously and different biases between regional and global NWP models. IMPROVER appropriately smooths probabilities by blending across spatial dimensions, validity time and model initialisation time, and using fuzzy thresholds when converting from ensemble members to probabilities. IMPROVER uses EMOS and reliability calibration to calibrate probabilities from each model so that probabilities are made compatible prior to multi-model blending. The IMPROVER task design separates per-model processing from final multi-model blending so that the most current available data are included in each output cycle.

IMPROVER provides a generational step in post-processing capability, enabling better use of the investment in high-resolution convection allowing ensembles and transferring those advances in science and computing into better quality public weather forecasts and information for decision support.

PROJECTED 21ST CENTURY CHANGES IN EXTREME WIND-WAVE EVENTS FROM AN ENSEMBLE OF GLOBAL OCEAN WAVE CLIMATE MODELS

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Extreme ocean waves shape world coastlines and significantly impact offshore operations. Climate change may further exacerbate these effects increasing losses in human lives and economic activities. Studies generally agree on the trends in the mean values, yet there is no consensus on the extreme events, and whether their magnitude and/or frequency are changing. The present work applies an innovative extreme value analysis approach (Breivik et al., 2013, 2014; Meucci et al., 2018) to a multi-model ensemble wind-wave climate dataset (Hemer et al., 2016), derived from seven global climate models, to evaluate projected extreme wave height changes towards the end of the 21st century. Under two greenhouse gas emission scenarios, we find that at the end of the 21st century, the one in 100-year wave height event increases across the scenarios by 5 to 15 % over the Southern Ocean. The North Atlantic shows a decrease at low to mid latitudes (5 to 15 %) and an increase at the high latitudes (10 %). The extreme wave heights in the North Pacific increase at the high latitudes by 5 to 10 % (*Meucci et al.*, 2020). The present work suggests that pooling an ensemble of future projected ocean storms from different GCMs might significantly improve uncertainty estimates connected to future coastal and offshore wave extremes, thereby improving climate adaptation strategies.

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WORK UNDERWAY IN THE R2O WATER MODELLING TEAM

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ABSTRACT NOT AVAILABLE

FORECASTING WATER AVAILABILITY AND DEMAND TO INFORM WATER USE AND MANAGEMENT

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Water is a highly valuable resource. Seasonal and short-term forecasts of water availability and demand could help users and managers of water resources make informed tactical and operational decisions. Currently, the Bureau of Meteorology provides seasonal and short-term streamflow and climate/weather forecasts. There is room to improve some of these hydroclimate forecasts. Future accessibility to forecasts of potential evapotranspiration or reference crop evapotranspiration will provide useful inputs to water demand forecasting.

Forecasting of water availability and demand is the next step in connecting hydroclimate forecasts with decision-making in water use and management. Many other complicated factors come into play, for example, water sharing and allocation rules, water trading, environmental water uses, water delivery constraints and river operations, and water user behaviours.

Research on methods for water availability and demand forecasting is being conducted through an ARC linkage project. The project partners include The University of Melbourne, Bureau of Meteorology, Murray-Darling Basin Authority, NSW Department of Planning, Industry and Environment, Goulburn-Murray Water, Lower Murray Water, Commonwealth Scientific and Industrial Research Organisation, and European Centre for Medium-Range Weather Forecasts.

In this presentation, we will provide an overview of research progress, including on seasonal and short-term forecasts of FAO56 reference crop evapotranspiration, embedding trend in seasonal streamflow forecasts, and seasonal and short-term water demand forecasts. We will give a detailed example on how seasonal streamflow forecasts can be used to make water allocation outlooks more accurate and less uncertain than currently available.

THE ACCESS CONTRIBUTIONS TO CMIP6

Simon Marsland[1], Dave Bi[1], Roger Bodman[1,2], Matt Chamberlain[3], Martin Dix[1], Peter Dobrohotoff[1], Ian Harman[4], Rachel Law[1], Andrew Lenton[3], Chloe Mackallah[1], Siobhan O'Farrell[1], Harun Rashid[1], Jhan Srbinovsky[1], Abhishek Savita[1,5], Arnold Sullivan[1], Ying Ping Wang[1], Matthew Woodhouse[1] and Tilo Ziehn[1]

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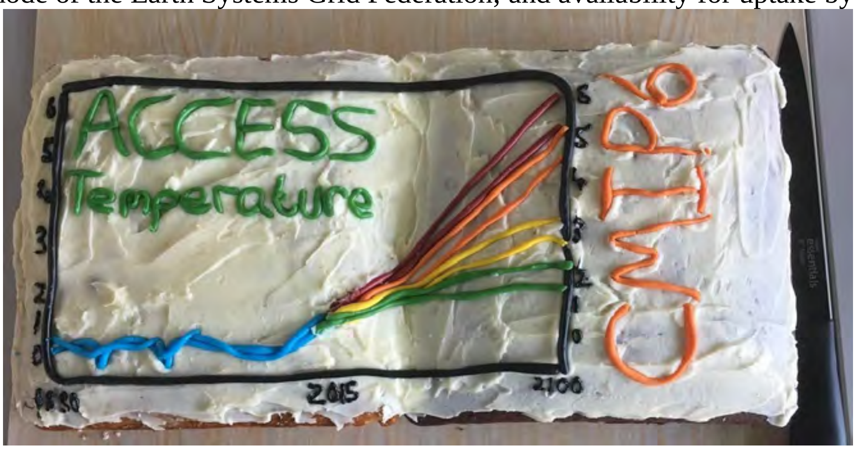
CSIRO and collaborators prepared two model submissions to the World Climate Research Programme's Coupled Model Intercomparison Project – phase 6 (CMIP6), supported by the National Environmental Science Program Earth Systems and Climate Change Hub. The two versions differ in their atmospheric component. ACCESS-CM2 (Bi et al., 2020) uses the GA7.1 Unified Model, while ACCESS-ESM1.5 (Ziehn et al., 2020) uses an older configuration. Both are run at N96 (1.875ºx1.25º) but with different vertical resolutions. They use the Australian land surface model, CABLE, the NOAA GFDL MOM5 ocean, and the LANL CICE sea-ice model. ACCESS-ESM1.5 simulates the carbon cycle, through a biogeochemistry module within CABLE and the ocean biogeochemistry model, WOMBAT. CMIP6 is the most comprehensive suite of climate modelling experiments ever conceived. In addition to entry level simulations, modelling groups were invited to contribute to a broad range of Model Intercomparison Projects (MIPs). We give an overview of the ACCESS CMIP6 contributions; their MIP participation; dataset availability via the National Computational Infrastructure node of the Earth Systems Grid Federation; and availability for uptake by new users.



The Official ACCESS CMIP6 Cake celebrated lower (ACCESS-ESM1.5) and higher (ACCESS-CM2) climate sensitivity model submissions to CMIP6. Icing indicates global mean surface air temperature anomaly trajectory from 0-6ºC (ordinate) for years 1850-2100 (abscissa). Historical 1850-2015 simulations (blue), and four CMIP6 lowest-to-highest future climate scenarios for 2016-2100 (green, yellow, orange, red). Serves 128 in parallel.

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COUPLED DATA ASSIMILATION IN THE CSIRO CAFE SYSTEM

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The CSIRO Climate Analysis Forecast Ensemble (CAFE) system is an Ensemble Kalman Filter data assimilation system developed to provide state estimates using a climate model (O'Kane et al, 2019). Coupled data assimilation is used for improved consistency, balance and better use of observations via their impact through the cross-domain error covariances. The CAFE system has grown to assimilate a wide range of global historical and real-time observations similar to other international systems. These encompass both infrared and microwave SST, altimetry, ocean in-situ data, sea-ice concentration and thickness, atmospheric (re)analysis data, ocean color and soil moisture. The CAFE system is unique, being the first global coupled large-scale geophysical DA system to assimilate into the four realms: atmosphere, ocean, land and sea-ice, to produce analyses consistent between these realms. Scale separation, sampling of cross-domain error covariances, model deficiencies and managing observation impact in coupled DA remains challenging. We address some of these issues by modifying the impact of observations via the cross-covariances (Sandery et al, 2020) and with asynchronous assimilation (Sakov, 2014). The DA system provides forecast innovation errors for a wide range of observations and sensors allowing for cross-validation. Minimizing these innovations in an overall global sense is a forecast model improvement. Model error and model representation of error (spread) remain a challenge, particularly for the deeper ocean, tropical atmosphere, stratosphere and sea-ice where low variability exists at the resolved scales. Improvements have been made to reduce bias in the forecast model using parameter estimation (Kitsios, et al, 2020), whilst simultaneously the CAFE system is being used to explore ensembles using weak perturbed sea-ice and ocean mixing physics and the use of an additional stochastic energetic forcing term within the ocean model for unresolved sub-grid-scale energy.

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PROGRESS WITH KM SCALE AND SUB-KM SCALE MODELLING FOR HIGH IMPACT WEATHER AND CLIMATE AT THE MET OFFICE

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Background

In the last 10 years or so, km scale convection permitting UM configurations have provided a step change in our forecast capability (Clark et al 2016) and many of the benefits pertain to forecasting of high impact events. The most obvious benefits involve convection but these models also assist in forecasting a number of other weather hazards. The same period has seen the start of work using convection permitting climate modelling, e.g. UKCP18 which have provided an insight into how weather related hazards may change in the future. Another important aspect of convective scale forecasting is ensembles. The MOGREPS-UK ensemble allows the modelling system to take into account uncertainty both due to larger scale predictability issues and also that due to the inherent lack of predictability on smaller scales.

Current Developments

A key area of interest for the km scale forecasting systems mentioned above is the representation of convection in the models. For both deterministic and ensemble systems it is essential to reduce the biases as much as possible. Across the UM Partnership a number of organisations are involved in the partnership Convection Working Group are working to systematically understand and reduce biases in the models. It is likely that many of the issues observed are related to the same fundamental deficiencies in the representation of convection. Work to enable 3d comparisons with observations and with idealised models will be key to understanding the nature of the deficiencies and their fundamental causes.

A second area of interest currently is the development of convective scale ensembles. A number of aspects of the MOGREPS-UK ensemble configuration have been upgraded in the last few years. An internal group (the “Spread PEG”) is working to understand this issue and develop techniques to improve the spread of MOGREPS-UK.

We are developing 100m “City Scale” models as part of the Met Office Research and Innovation Strategy. 100m scale models are expected to improve the representation of many meteorological phenomena (including convection) however a particular benefit is expected to be in forecasting hazards in urban areas (flooding, heat, air quality etc). The representation of the urban surface is a challenging problem which was initially addressed by a focused workshop in 2016 (Barlow et al). Three key areas for development are the surface energy balance scheme, anthropogenic fluxes and a vertically distributed canopy scheme.

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A VISION FOR NUMERICAL WEATHER PREDICTION IN 2030

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In this essay, I outline a personal vision of how I think Numerical Weather Prediction (NWP) should evolve in the years leading up to 2030 and hence what it should look like in 2030. By NWP I mean initial-value predictions from timescales of hours to seasons ahead. Here I want to focus on how NWP can better help save lives from increasingly extreme weather in those parts of the world where society is most vulnerable. Whilst we can rightly be proud of many parts of our NWP heritage, its evolution has been influenced by national or institutional politics as well as by underpinning scientific principles. Sometimes these conflict with each other. It is important to be able to separate these issues when discussing how best meteorological science can serve society in 2030; otherwise any disruptive change - no matter how compelling the scientific case for it - becomes impossibly difficult.

LONG LEAD PREDICTION OF THE 2019 CLIMATE EXTREMES

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The largescale circulation during the latter half of 2019 was characterized by record-strength Indian Ocean Dipole, Antarctic stratospheric warming, and negative SAM (Southern Annular Mode). A central Pacific El Nino had also developed. Each of these phenomena have been demonstrated to promote hot and dry conditions across much of Australia during the spring and early summer seasons. Reflecting this unique combination of events that developed in 2019, Australia experienced record warm and dry conditions during spring 2019 through early summer 2020. Using historical relationships, we show that the dry and hot conditions were well accounted for by the evolution of the India Ocean Dipole, the Modoki El Nino and the Antarctic stratospheric warming with its associated weaker polar vortex especially over eastern Australia. That analysis suggests that the anomalous conditions across eastern Australia during 2019 should have been highly predictable.

Using the ACCESS-S1 coupled model subseasonal-seasonal prediction system, we show that the weakening of the stratospheric polar vortex beginning in late winter and associated development of negative SAM during spring were well predicted from as early as mid-winter. Although the precise timing of the onset of the SSW was not predictable beyond about 2 week lead time, the much weaker than normal polar vortex and associated downward coupling to negative SAM during late spring was highly predictable more than a month in advance. The development of the positive IOD and its teleconnections to Australia were also predictable from mid-winter, consistent with predictability of the IOD based on analysis of the hindcasts. The Modoki El Nino, which is more persistent than the IOD, and its teleconnection were well depicted in the model from as early as May 2019.

An interesting finding is that the development of negative SAM as a result of downward coupling from the polar stratospheric warming was erroneously and systematically predicted to occur too early throughout September and early October. In reality, negative SAM did not develop until the 3rd week of October. We attribute this too-early predicted development of negative SAM to systematic errors in the depiction of the teleconnection to high latitudes from the Indian Ocean Dipole.

EVENT ATTRIBUTION WITH S2S SYSTEMS

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An extreme event dynamically forecast on a sub-seasonal to seasonal timescale can be re-forecast with altered initial conditions and setting a lower CO_2 level to represent that same event as if it occurred in a climate without industrialisation. This provides the basis for an event attribution system, where we can attribute the change between the two forecasts to the influence of increasing levels of greenhouse gases in the atmosphere and the impact they have had on the climate system to date. This provides the potential for attribution statements to be made about any type of event that can be well forecast, as well as the capacity to understand the dynamics behind the development of the extreme nature of the event, and changes seen in those. It also provides the potential for delivering real-time attribution statements.

To alter the initial conditions, a 'delta' is defined that represents the changes in the atmosphere, ocean and land due to increasing levels of greenhouse gases over the last 60 to 100 years. This is then applied to the initial conditions and a forecast using a coupled ocean-atmosphere dynamical sub-seasonal forecast system is made (Wang et al. 2020). The method to identify the 'delta' requires a number of steps, and these can be different depending on the system used. Using POAMA, (the Bureau of Meteorology's operational seasonal forecast system until recently), the method builds on long initialized free-running integrations of POAMA, however, for ACCESS-S (the current operational system), five long simulations of the CMIP5 model, HadGEM3-GC2, are used to estimate the pre-industrial and 'current' conditions. The difference between these periods serves as the delta.

In this presentation preliminary results using both systems will be illustrated by examining the heatwave preceding the Black Saturday fires in south-east Australia in 2009 – how the heat developed in each forecast, and the results in the lowCO_2 world compared to the real-world forecast, and what final attribution statements might be made.

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CLIMATE MATES: CONNECTING THE BOM AND GRAZIERS IN NORTHERN AUSTRALIA

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Background

Much of northern Australia has highly variable rainfall and is prone to both droughts (or failed wet seasons) and floods, which can seriously impact the red meat industry in this area. The Northern Australia Climate Program (NACP) began in 2018 and is tasked with furthering and communicating climate science for the red meat industry in northern Australia. To accomplish this, NACP is composed of three components: Research, led by the BOM and the UKMO; Development, led by the University of Southern Queensland (USQ); and Extension, also led by USQ. Climate Mates, regionally located extension officers, are critical to the knowledge transfer of climate information from researchers to red meat producers.

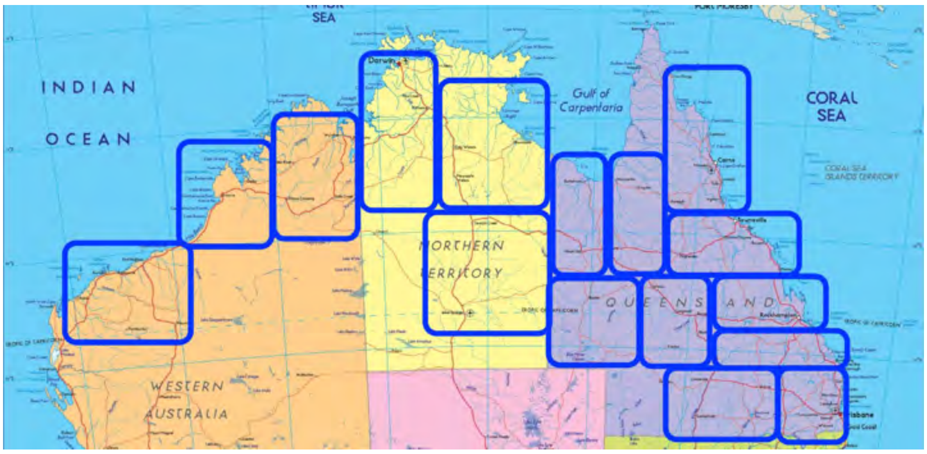
Methods

The Climate Mates were hired not for their climate knowledge, but rather for their industry knowledge, local networks, and communication skills. An initial week-long intensive climate training included presentations from NACP-BOM and NACP-UKMO researchers, which not only imparted knowledge, but also built relationships. The Climate Mates provide an extension service in their region including field days, newsletters, social media, and workshops that incorporate climate researchers to provide a two-way flow of information between primary producers and researchers.

Results and Conclusions

The Climate Mates have successfully gained climate knowledge, are communicating that knowledge to producers in their area, and provide feedback to the BOM and UKMO regarding how producers use weather and climate information. The program was so successful that it was doubled in size, from eight to 16 Climate Mates, in 2020, with Climate Mate regions shown in the figure.

To date, NACP-BOM researchers have participated alongside the Climate Mates in over 10 NACP climate workshops with producers, across Queensland, Northern Territory, and Western Australia. Due to COVID, BoM researchers have recently contributed to 16 digital eTraining climate modules for Climate Mates and four modules for producers.



NACP Climate Mate regions

PLACING THE USER AT THE HEART OF INNOVATIVE EARLY WARNING SERVICES

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The creation of user-oriented services is common practice in different sectors, both public and private. The innovation of services based on scientific knowledge has been transitioning for years to new forms and methodologies that try to incorporate the view of the beneficiary of these solutions through the collection of needs from a critical and interdisciplinary perspective.

The WMO endorsed Alert.Ar Project has inaugurated in the National Meteorological Service of Argentina a new way of addressing the needs of users who use weather and climate services to mitigate the impacts of severe events. Since 2015, a small group of social sciences junior researchers have been working to identify opportunities to improve the NMS's early warning system, and in five years they have become a stable body within the NMS. The knowledge acquired in that experience not only managed to collect the users' voice in detail but also to establish new interdisciplinary ways of working that today are reflected in a recently pre-launched early warning system that incorporates these voices.

What do our users say about the information services that science provides? What preconceptions does the scientific system hold when it comes to providing solutions to citizens? What are the interdisciplinary methodologies that can be incorporated into meteorological services to provide useful services? How do we incorporate the knowledge of the user who makes decisions based on our service, considering that these decisions can save lives? Or better, where would we start if we could radically change an early warning system? This presentation will attempt to collect the most relevant aspects of the work carried out by the Meteorology and Society department from Project Alert.Ar in 2015 to the establishment of a new early warning system in 2020 and provide the knowledge acquired on strengthening science-based services created from transdisciplinarity.

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USING EXTREME/COMPOUND EVENTS IN RISK ASSESSMENTS – AN EXAMPLE FROM THE ELECTRICITY SECTOR CLIMATE INFORMATION (ESCI) PROJECT

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The Electricity Sector Climate Information (ESCI) project is looking to improve the reliability and resilience of the National Electricity Market against the risks from climate change and extreme weather. The project is co-designing tailored climate change data and information to ensure it is usable by the people who need it, to support improved long-term climate risk planning for electricity infrastructure. The work is funded through the Department of Industry, Science, Energy and Resources and is being undertaken by CSIRO and the Bureau of Meteorology in collaboration with the Australian Energy Market Operator (AEMO).

This presentation explores a compound extreme scenario developed by the ESCI team for use by the energy sector.

OBSERVATIONS OF PRECIPITATION OVER THE SOUTHERN OCEAN

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Precipitation over the Southern Ocean (SO) remains a major barrier in better understanding the coupled Southern Ocean Climate System (e.g. Manton et al. 2020). Estimates of the average precipitation rate across the entire SO can differ by over 100% or 1 mm day^{-1} with the most recent satellite products revealing that these differences are evident at both lower latitudes (40° - 50°S) and higher latitudes (50° - 65°S). Since 1 mm day^{-1} precipitation must be balanced by 26 W m^{-2} latent heating, errors in the precipitation rate directly contribute to large biases in the energy budget over the SO and the SO sea surface temperature that continue to be found in both climate simulations and reanalysis products. While many reanalysis products link the SO precipitation to frontal passages, observations from Macquarie Island find that post-frontal precipitation makes a substantial contribution (e.g. Lang et al. 2018; Lang et al. 2019).

In this talk we examine marine boundary layer clouds and precipitation observed in a sustained period of open mesoscale cellular convection (MCC) over the Southern Ocean using CAPRICORN 2016 shipborne observations, Himawari-8 cloud products. The shallow convection was characterized by the presence of supercooled liquid water and mixed-phase clouds in the sub-freezing temperature range, consistent with earlier in-situ observational studies where ice multiplication may be active in producing large quantities of ice in open MCC clouds. Ice-phase precipitation was observed to melt below cloud base with evidence of cool pools produced in a decoupled boundary layer.

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FORECASTING THE EXTREMES: AUTOMATION OR MANUAL INTERVENTION FOR HIGH END RAINFALL EVENTS

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The Bureau of Meteorology weather forecast service includes gridded daily probabilistic rainfall forecasts for lead times of one to seven days across an Australian domain. Forecast parameters include the chance of any rain, the mean rainfall amount, and various rainfall exceedance forecasts. These forecasts are used by a wide range of groups within the Australian community, including hydrologists, dam operators and emergency services in potential flood events.

These rainfall forecasts are issued via the Graphical Forecast Editor (GFE) and are typically generated in one of two ways. The first method is to accept the output of a fully automated forecast system known as OCF, which is a calibrated poor man's ensemble (Bureau of Meteorology, 2018). This is the *automated* approach. The second method is for operational meteorologists to produce their own predictive rainfall distributions. This is usually achieved by using a manual blend of select numerical weather prediction forecasts, performing additional modifications and then applying statistical tools available within the GFE. This is the *interventionist* approach. The Bureau of Meteorology is quickly moving towards an operational model where many meteorologists are being deployed for tasks other than forecast production, and consequently an increasingly higher proportion of forecasts are issued using the automated approach (Just, Foley, 2020).

In this presentation, we look at the historical quality of automated and interventionist forecasts for high end rainfall events (either forecast, observed, or both). The overall accuracy of their predictive distributions is assessed, along with bias characteristics, for different parts of Australia. For some geographical areas, the automated system has performed relatively well, while for other areas (notably eastern NSW) it has substantial under-forecast biases.

In addition to comparing historical forecasts generated by the automated and intervention approaches, we also assess the performance of some simple systematic, interventionist techniques, which could be semi-automatable and implemented within forecast productions.

The results of this study suggest that there is substantial room for improvement in the quality of the automated forecast system that is currently deployed to operational forecast production in forecasting extreme rainfall events, and puts forward the case that there is still a place for developing evidence-based interventionist forecasts strategies in such situations.

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CONNECTIONS OF CLIMATE CHANGE AND VARIABILITY TO LARGE AND EXTREME FOREST FIRES IN SOUTHEAST AUSTRALIA

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The 2019/20 Black Summer bushfire disaster in southeast Australia was unprecedented: the extensive area of forest burnt, the radiative power of the fires, and the extraordinary number of fires that developed into extreme pyroconvective events were all unmatched in the historical record. Australia's hottest and driest year on record, 2019, was characterised by exceptionally dry fuel loads that primed the landscape to burn when exposed to dangerous fire weather and ignition. The combination of climate variability and long-term climate trends generated the climate extremes experienced in 2019, and the compounding effects of two or more modes of climate variability in their fire-promoting phases (as occurred in 2019) has historically increased the chances of large forest fires occurring in southeast Australia. Palaeoclimate evidence also demonstrates that extreme fire-promoting phases of tropical Pacific and Indian ocean variability are now unusually frequent compared with natural variability in pre-industrial times. Indicators of forest fire danger in southeast Australia have already emerged outside of the range of historical experience, suggesting that projections made more than a decade ago that increases in climate-driven fire risk would be detectable by 2020, have indeed eventuated. The multiple climate change contributors to fire risk in southeast Australia, as well as the observed nonlinear escalation of fire extent and severity, raise the likelihood that fire events may continue to rapidly intensify in the future. Improving local and national adaptation measures while also pursuing ambitious global climate change mitigation efforts would provide the best strategy for limiting further increases in fire risk in southeast Australia.

MACHINE LEARNING FOR IMBALANCED DATA – LIGHTNING AND DROUGHT FORECASTING

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Lightning and drought are just some examples of high impact extreme weather and climate events that have lasting impacts on our society, economy and environment. Because of the irregularity of events such as drought, and the binary nature of lightning, climate and weather models struggle to predict such phenomena with a reasonable level of accuracy. Furthermore, models generally struggle to predict the intensity and duration of such events – the recent upper North Island drought (2019-2020) is one example of this. In this talk we will discuss the machine learning approaches NIWA is using to complement Numerical Weather Prediction (NWPs) and seasonal climate forecast models in order to forecast both lightning and drought.

Forecasts of lightning in NWPs are often determined using various criteria in variables such as the graupel flux (modelled). However, a forecasting approach using a single variable alone may be limiting, as additional predictive information might exist in other modelled fields such as air temperature, boundary layer height etc. Furthermore, a threshold-like parameterisation of lighting does not consider how the variability of atmospheric fields in time may affect lightning. Through training a Convolutional Neural Network (CNN) on the forecast NWP modelled fields (e.g. air temperature) against observations of lighting, our model can extract the most important features in these fields that are relevant to the prediction of lightning. Our initial results indicate significant improvement over currently used NWP lightning forecasts. The forecasts have fewer false positives and an increased precision for the temporal window in which lightning occurs.

A relatively similar approach is applied to drought forecasting, where a variety of observed atmospheric circulation indices are used in conjunction with a sufficiently long lagged history of the variable in a CNN model in order to forecast either precipitation anomalies or a drought index at one point in time. Our results are very promising, producing accurate hindcasts of the 2019-2020 upper North Island drought. Furthermore, our analysis indicates that maximum forecast accuracy is achieved with a 64-month lagged history for each of the circulation indices – indicating that there is likely a memory effect in atmospheric circulation that is useful for drought forecasting.

The future of machine learning is bright for climate/weather forecasts, as operationalized forecasts of drought and lightning could be extremely useful supplementary information to weather forecasters – and in turn can help make better forecasts of extreme events. Furthermore, by using recent developments in interpretable machine learning, we may be able to learn more about the physics of extreme events such as drought and lightning.

DEVELOPING A MULTI-SCALE EARLY WARNING SYSTEM FOR AUSTRALIA'S COASTAL FLOODING AND EROSION HAZARDS

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Coastal storms are a persistent threat to livelihoods and assets along Australia's coastlines. By delivering timely information about a coastal storm event, early warning systems (EWSs) can enhance community preparedness, reducing the loss of life, property, and critical infrastructure along coastlines.

EWSs need to optimize for both efficiency and accuracy when communicating the timing and severity of an anticipated hazard. Current state-of-the-art EWSs for coastal flooding and erosion often rely on existing hydrometeorological, process-based model forecasting chains that simulate barometric pressure, winds, waves, and water levels at global and/or regional scales (e.g., CoSMoS, Emilia-Romagna EWS; Barnard et al., 2014; Harley et al., 2016). These forecasts provide the critical forcing for down-scaled, local flooding and erosion predictions. Most coastal hazard EWSs are centered on forecasting coastal flooding risks, which predominantly affect low-lying, surge-dominated coastlines (e.g., the US East coast, Atlantic-facing European coastlines). However, much of Australia's densely populated coastlines are wave-dominated, where erosion hazards feature much more prominently.

Efforts to forecast erosion hazards can be categorized under three main approaches. The first approach uses forecasted hydrodynamic parameters (e.g., water levels, wave parameters) as proxies to efficiently predict the degree of erosion along a beach profile. The second involves more intensive process-based modelling of erosion at the beach profile scale (e.g. CoSMoS). Finally, emerging techniques involve data-intensive and/or machine learning methods for relating forecasted storm characteristics to erosion severity (e.g. CoSMoS).

This project aims to develop multi-scale, coastal hazard EWS capabilities for Australia. This fully integrated EWS will implement state-of-the-art scientific methods for predicting both flooding and erosion impacts caused by coastal storms. Two prototype coastal hazard EWSs will be developed using the Delft-FEWS forecasting platform: one on Australia's east coast (Narrabeen) and one on the west coast (Mandurah). The project will build upon the foundation of previous work to explore more rigorous and novel methods for predicting erosion severity on Australia's coastlines. In particular, there will be significant interaction with potential end-users throughout the duration of the project, which will inform the nature, timing, and format of these erosion hazard predictions. We also aim to develop new methods for incorporating uncertainty predictions into our erosion forecasts.

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UNDERSTANDING FLASH DROUGHTS AND THEIR PREDICTABILITY

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Flash drought is a term used to describe a drought that has undergone rapid intensification. Due to its rapid nature, the impacts of flash droughts will likely occur too quickly for many of the usual drought-coping mechanisms to be deployed. In Australia, the term was first used in reference to periods of rapidly intensifying drought during 2017 and 2018 in eastern Australia (Nguyen et al 2019). The evolution of flash drought can successfully be monitored using the Evaporative Stress Index (ESI) computed over a 4-week running window on a 5km grid from outputs of the Bureau's water balance model AWRA-L. The 45-year historical period of 1975-2019 is chosen to analyse the climatology of flash drought over Australia, while predictability of flash drought is examined using the Bureau's dynamical forecast modelling system ACCESS-S1 and the AWRA-L hydrological forecasting system.

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NEW CAPABILITY FOR FORECAST VERIFICATION

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Verification is an integral part of forecast service provision. It provides insights into the quality of current forecasts and also supports objective improvements for future forecast services. Good, shared tools for verification allow more time for science rather than the mechanics of setting up the calculations. We will compare and contrast two software systems for verification which are emerging in the Bureau with the support of its Public Services Transformation program. One of these, Jive, has been developed in house, while the other, METplus, comes from the National Center for Atmospheric Research in the US.

Jive was developed in the Bureau's Research section to enable evidence-based improvement of our 7-day public weather forecasts. It has also allowed forecaster examination of daily verification results and organizational tracking of performance of the Bureau's public weather forecasts over time. The system primarily uses surface automatic weather station observations as ground truth and has corresponding forecasts from the Graphical Forecast Editor (GFE) and some third-party providers. It has a range of Python libraries that can be used for ad-hoc data analysis within web notebooks, and a series of curated dashboards with verification results. The dashboards show comparisons between the issued Bureau forecasts and automated alternatives and have supported improvement to standard operating procedures and to the automated forecast guidance. The system continues to be extended and is being moved from research systems onto operationally-supported platforms within the Bureau.

METplus is being used by many international organizations and is being adopted by the UK Met Office with whom the Bureau collaborates on Numerical Weather Prediction (NWP) modelling. It has a wide range of spatial verification techniques, which the Bureau intends to harness to allow enhanced verification of its convection-allowing NWP models and to assess the new high-resolution National Analysis Scheme which is currently under development. Potential applications for verification of area-based warning products will also be explored. Early trialling of METplus in the Bureau is getting underway.

Jive and METplus are both modular and inhabit a similar Python ecosystem, so there may be crossover opportunities. We are keen to explore collaboration with NCAR and the UK MetOffice opened up by shared tools. The two systems promise to facilitate many verification activities in the Bureau in coming years which contribute to better future services.

HYDROLOGY SCIENCE PLAN OF THE BUREAU OF METEOROLOGY – PRIORITIZATION PROCESS AND POTENTIAL FUTURE DIRECTIONS

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ABSTRACT NOT AVAILABLE

NATIONAL GFE: HOW RESEARCH IS SUPPORTING THE MOVE TO NATIONAL PRODUCTION

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The Graphical Forecast Editor (GFE) underpins the Bureau's forecasting services, allowing forecaster intervention in model guidance to produce forecasts. The Bureau originally adapted the GFE to reflect a geographically distributed operating model. Now the Bureau is moving towards a model of resilient national operations (RNO) and will require a National GFE, producing forecast products for the entire country. Current instances of GFE operate at a nominal grid resolution of 6km, with the exception of TAS and VIC instances which operate at 3km. The National GFE will also eventually operate at 3km resolution across all states and territories.

Scientists and software developers have been involved in close collaboration to implement the move to a National GFE. This requires a major IT uplift and also presents a variety of forecast process challenges to be worked through.

We will illustrate solutions arrived at for a number of problems worked on within the Research section, including:

- handling local time of day issues when editing grids across a national domain;
- contending with multiple time zones for daily gridded products;
- incorporating multiple limited area ACCESS-C3 NWP models into composite national grids;
- reconciling different service definitions in use by different forecast offices, for the example of representing swell in the Gulf of Carpentaria.

ENABLING BETTER DECISIONS

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Every year, despite increasingly accurate forecasts, Australians lose their lives, property or livelihoods as a result of the impacts of natural hazards. Our weather, water, climate and ocean information services on their own are insufficient to drive informed decisions, and the connection between a hazard, its impact and the appropriate response is not always obvious to our customers.

To help address this, the Bureau is moving from its traditional hazard forecasts towards forecasting the impacts of those hazards. In this way, we can help our customers, partners and stakeholders act on the deep knowledge the Bureau has developed over its 100+ year history. In future, we will be better able to protect lives, properties and livelihoods by predicting what the weather does, rather than what the weather is.

In response to these challenges we have embarked on the Australian Safety Alerting Program (ASAP). The vision for ASAP is a multi-hazard, impact-based forecast, warning and alerting capability that will provide new capability to help our decision support teams to work more closely with their customers across timescales, and provide alerts, data and customisable information tailored to users. Through ASAP, we will be able to reach the right people, through the right channels, at the right time, with the right information, to prompt the right response.

IMPACT FORECASTING AND WARNINGS - WHAT ARE THE NEXT STEPS

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We often talk about the desire to achieve the ‘last mile’ and how we could narrow the gulf between ‘science and action’. It was this desire that provided the catalyst for change and the move to impact-based thinking. The core tenant in this paradigm shift was to provide the reason and rationale for change, to bring very differing communities together, to provide the mechanisms and collective desire to make a difference on the ground, to save lives, reduce distress and disruption. But what next – what is the future and what can we learn from the past?

The most valuable part of impact-based warnings is the personal relationship between partners, which creates a level of trust enabling quick decision making under pressure. This is both a strength and a weakness as it implies that any gap in those relationships could dramatically weaken the overall impact of the warnings. It also suggests that citizen trust may be dependent on who delivers the information and what form of relationship they have with the user.

Our warnings are often focused on single hazards and their direct consequences. People living in well built homes, in urban settlements, generally have little to fear from the direct impacts of most hazards (except perhaps flood). However, urban populations, particularly those megacities residing along coastal districts can be extremely vulnerable to indirect impacts such as loss of power, water, communication, transport and even food. And this at the time of great environmental and societal change.

Therefore, against this backdrop, we may wish to move towards a multi-hazard, ensemble orientated, ‘event-based’ approach in the future that captures compound and cascading (linked) hazards and impacts to better inform actors of the event risk – helping to support better overall decision making and prioritisation. Such a vision would be ambitious and scientifically challenging but would represent a hugely valuable step change in impact-based forecasting and warning, supporting improved response and building long-term resilience (the mantra of ‘build back better’ springs to mind here!).

As an Operational Meteorologist, I would also ask what role we play going forward? We are constantly asked the question ‘what defines a good meteorologist? What characteristics and performance levels do we expect from us? How do we measure the value add to decision making and how much do we play in building even stronger user satisfaction? These aspects are becoming increasingly acute in defining the next steps. In order to improve impact-based services we need to better understand the benefit value to our users; perhaps this requires a shift from absolute to perceived performance measures and a framework that enables agile, co-designed, partner-based development activities to explore and exploit our national capabilities. This is likely to be the next paradigm shift in our desire to achieve the ‘last mile’ – one that embraces further change based on continuous improvements, agreed user perspective performance measures and business value.