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FOREWORD

Weather and climate have an enormous impact on human society, influencing almost every activity undertaken. As such, societies have a need to understand and predict the weather in order to gain knowledge about its potential effects on the lives and livelihood activities of their citizens. The amount of information about the state of the atmosphere is accelerating exponentially, with improved modelling approaches, new observational capability, and advanced information technology and data processing. However, simply providing access to this information obtained from these sources is not enough to provide a modern weather service. To be useful, the information needs to be translated, via scientific applications, into specific knowledge that can subsequently be used to inform decisions.

There are multiple aspects around applications of weather and climate science that need to be considered to ensure that they (continue to) generate added value. New discoveries and approaches to the underlying science need to be incorporated into the applications. Advances in computing technologies and methodologies need to be effectively utilized to efficiently tackle larger quantities of increasingly sophisticated data. The evolving needs of the end-users of the applications must also be considered. The intersection between science and service lies at the heart of the creating effective applications of weather and climate science.

The primary aims of the workshop are to provide an overview of weather and climate applications at the Bureau of Meteorology and globally, exploring the intersection between science and service. The focus will not only be on the science and technology behind the applications, but also on how they generate added value. State-of-the-art applications will be described, and users of the products will have the opportunity to provide their perspectives. A particular emphasis of the workshop will be on the future development of weather and climate applications and how we can take advantage of near-term improvements in technology, modelling and observations.

The broad themes and associated questions for the workshop are:

- **Current status and plans of Bureau systems and infrastructure.** Where are we today and what does the future hold in terms of observation, modelling and computing infrastructure?
- **Machine learning.** As information availability increases, more automation and computer assistance is required. What are the optimal techniques for doing this? What are some successful examples and what should we strive for?
- **Effectively exploiting observational capability.** How are we utilizing new observational capability from satellites, ground-based sensors, and other observational platforms? What impact have recent improvements in the collection of observations had on weather and climate applications? What further improvements are needed?
- **Advanced simulation.** How are numerical model ensembles and high-resolution (convection permitting) models improving the accuracy and utility of numerical forecasts? How are these best incorporated in forecasting operations? What does international best practice look like?
• **Weather and climate applications.** Examples abound in a variety of areas, including aviation, energy and resources, health, emergency services, agriculture, water and flood, ocean and marine services and climate adaptation. How does science inform these applications? How do users influence and utilize these products?

• **Impacts and value of applications.** How do we understand the impacts and value of applications to Bureau services and products? How do we identify user needs and incorporate these in the development and utilisation of applications? How do we maximize the impacts and value of the applications we deliver along the end-to-end, science to service, value chain?

We are pleased to welcome the prominent scientists and experts from overseas, Australian research agencies and universities who have been invited to give keynote presentations, including

• Katie Antypas  
  *National Energy Research Scientific Computing Center*

• Phil Brown  
  *Cray UK*

• David Gagne  
  *Advanced Study Program, National Center for Atmospheric Research*

• John Handmer  
  *RMIT University*

• Peter Hayman  
  *South Australia Research and Development Institute*

• Alistair Hobday  
  *Commonwealth Science and Industry Research Organisation*

• Israel Jirak  
  *National Oceanic and Atmospheric Administration, Storm Prediction Center*

• Martin Kearns  
  *Innodev*

• Andrew King  
  *University of Melbourne*

• George Kuczera  
  *University of Newcastle*

• Jeff Lazo  
  *National Center for Atmospheric Research, Research Applications Laboratory, USA*

• Tom McMahon  
  *University of Melbourne*

• Ken Mylne  
  *United Kingdom Met Office, UK*

• Mike Pavolonis  
  *National Oceanic and Atmospheric Administration, National Environmental Satellite, Data and Information Center*

• Michael Scheuerer  
  *Cooperative Institute for Research in the Environmental Sciences, National Oceanic*
The workshop is hosted by the Bureau of Meteorology (BoM) and is sponsored by BoM, CSIRO, CRAY, DDN Storage, Xenon Systems and the National Computational Infrastructure. I would like to thank these sponsors for their generous support of the workshop. As chair of the workshop organizing committee, I would like to genuinely thank the members of the organizing committee for their hard work and effort: Linda Anderson-Berry, Beth Ebert, Val Jemmeson, Leon Majewski, Rod Potts, Tim Pugh, Harald Richter, Claire Spillman, Samantha Stevens, Blair Trewin, Narendra Tuteja, and Gary Weymouth. I would also like to thank Keith Day, Anu Arora and Ian Smith for their assistance.

Chris Lucas

Bureau of Meteorology
ECONOMIC ASSESSMENT OF HYDROLOGICAL-METEOROLOGICAL SERVICES AND PRODUCTS: THE VALUE CHAIN APPROACH

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Introduction

Weather related hazards such as typhoons, floods, heat waves, wildfires, droughts, and tornadoes cause billions of dollars of damage and affect millions worldwide in both developed and developing countries. Guha et al (2015) report that between 2004 and 2013 an annual average of 127 meteorological, 32 climatological, and 192 hydrological disaster affected an average of 191 million people each year, and caused an average annual $122 Billion dollars of damages. “Day-to-day” events (not considered “disasters”) likely have an even larger aggregate impact on society and affect virtually everyone on the planet in some manner every year. While not all (or perhaps even most) of the impacts can be avoided or mitigated, with appropriate information systems and processes there are undoubtedly significant societal benefits of geospatial information on weather, water, and climate.

After some brief thoughts on why economic analysis is relevant to the hydro-met community, I present some concepts on data, information, and knowledge. I discuss what the value of information (VOI) means from this economist’s perspective and present the “Weather Information Value Chain” as a tool for understanding the creation of value from hydro-met information. I conclude with an example of valuation of hydro-met information in the context of a value chain from a recent research effort to improve weather forecasting of solar power generation for energy utilities in the United States.

Background

As noted in the recently published WMO, WBG, GFDRR & USAID (2015) guidebook on socio-economic benefit assessment for national meteorological and hydrological services (NMHS), Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services, there are a number of reasons NMHS (and others) should or do undertake economic analysis including:

- Program evaluation / program justification such as:
  - Validating the provision of basic met/hydro services
  - Validating past and current investments in specialized met/hydro services
  - Justifying new investments in met/hydro services
- Determining the value of NMHSs to user goals, and
- Prioritization or reallocation of resources

As a social scientist, I also argue that economics as a study of human behavior and decision making can help NMHS and others understand the weather related decision making process and
help NMHSs to enhance product development, communication approaches, and ultimately decision making to increase societal value. While not discussed here, I also feel there is a significant opportunity for the application of newly developing concepts from behavioral economics and related studies (see Kahneman, 2011) to understanding behavior and decision making to further enhance societal value – and to help understand weather-risk “conundrums” such as why some people do not protect themselves adequately from environmental hazards.

**Value and the Value of Information (VOI)**

The term “value” means different things to different people but in general can be taken as a measure of some sort of objective function. From a neo-classical economic perspective, value ultimately relates to and is measured as the well-being of individual members of society. When considering the value of hydro-meteorological products and services we are trying to determine how those products and services (i.e., hydro-met information) increase the well-being of the members of society. Hydro-met information has value if it allows individuals to achieve greater “expected utility.” This means that given potential weather outcomes and actions individuals could take given expected weather outcomes, using the information increases the probability-weighted outcomes given the decisions they made. Value of Information (VOI) is a concept from economics for measuring the value of information has in informing decisions under conditions of uncertainty.

**Data, Information, and Knowledge**

More rigorous approaches to defining and characterizing the creation and “transfer” of information would help the weather community better understand the value creation process. What may be considered as “data” to one user may be “information” to another depending on the decision context (Floridi 2010).

- Data is facts and figures without interpretation or analysis (e.g., raw sequence of symbols) Data is a stock.
- Information is data that has been interpreted so that it has meaning for a user – information has semantic content. Information is a flow variable.
- Knowledge is the understanding of the world that allows us to convert data to information as well as to use information to make decisions. Knowledge is a stock variable.

A very broad set of factors are useful in understanding and characterizing information including taxonomical approaches defining intrinsic, relational, and reputational characteristics (Stvilia et al. 2007). Common measures of the quality of hydro-met information such as accuracy and precision are only subsets of representational aspects of relational metrics. There has been little work characterizing and evaluating a broader set of metrics of hydro-met information across all links in the value chain as the format and content of information changes substantially.

**Tying It All Together: The Weather Information Value Chain**

Figure 1 presents the conceptual model of the “Weather Information Value Chain.” At the left-hand side, observational systems gather environmental data that are used in models to create forecasts and warnings (i.e., information). This information is then disseminated through
multiple channels and likely altered by secondary information providers (e.g., private weather services, media channels such as television and radio) and communicated to end-users. End-users may (or may not) then use this information to make decisions about an uncertain future. In the context of using information to improve or change the decisions of end-users, economists would argue there is economic value to this information.

The economic impacts of weather are “outcomes” that occur with the actualization of weather events (which is not causally related to weather information) and the decisions made by end-users. Weather information has the potential to change decisions prior to the actualization of the weather event and potentially change outcomes. The value of weather information is the expected value of changes in outcomes following from changes in decisions based on that information – before the weather actualization. Weather information thus has ex ante value whereas the economic impacts of weather are ex post measures of weather occurrences – not of information.

Figure 1: Weather Information Value Chain

I propose that the value chain concept provides a useful approach to understanding and discussing the entire process of information creation, communication, and use – even if there is not a specific valuation component in the discussion. From an economic analysis perspective I also advocate that it is useful, if not actually necessary, to adequately characterize the entire value chain process and apply appropriate information quality measurements along the chain in economic studies to ensure that value estimates of hydromet information are valid and reliable. Without a solid “chain of evidence,” valuation studies are black boxes wherein the quality the study and any results can be questioned. The degree of rigor necessary in developing, characterizing, and quantifying the process depends ultimately on the purpose of the economic study and the use of the resulting value estimates.

The weather information value chain can also be used to detail the potential contributions of other social sciences to evaluating the chain and to enhancing value. Studies from other social sciences of information creation, communication, decision making, risk perceptions, impacts, etc. can further improve our understanding of the overall process and identify priorities for improvements.

Finally, the weather information value chain could be used as a tool to explicate how user-relevant information can drive product and service development. Having valid measures of economic value of different information products and services – tied to common metrics of hydromet information quality such as skill scores – can provide quantitative evaluation information quality from the end-users perspective or guidance on priorities for information enhancements.
Value of Information Characterization and Evaluation – VOICE

I propose the VOICE concept as a set of tools and methods from the social sciences to “build” the value chain in any given hydro-met information project. The first component of the VOICE approach is using the concepts of objective functions, resources, and constraints to frame the process of information use (i.e., decision making). This involves determining what the objective (formal or implicit) of each stakeholder is, what resources they have to input into meeting that objective, and what constraints they face in meeting their objective. The second component of the VOICE approach is the broad range of tools and methods from the social sciences to elicit the components of the value chain. These tools include literature reviews, focus groups, surveys, expert elicitation, cognitive interviews, mental modeling, and observational methods. Each of these methods is founded on extensive principles and practices and requires significant expertise to implement appropriately. Recognizing and characterizing that different stakeholders have different objectives, resources, and constraints can improve our understanding of the value creation process as well as lead to identifying gaps and opportunities to improve the process.

Case Study: DOE Solar Production Cost Modeling

Figure 2 shows the information value chain developed by Sue Haupt (Haupt forthcoming), principal investigator of the Department of Energy funded project “A Public-Private-Academic Partnership to Advance Solar Power Forecasting.” The goal of this research-to-applications project was to develop a solar power forecasting system advancing the state-of-the-science linking meteorology and power forecasting for large-scale solar energy systems. This work involved efforts across the whole range of the value chain including advances in the state of cloud forecasting that is translated into solar irradiance and power forecasting. The project advanced the ability to reliably forecast solar energy as part of the overall power mix with an ultimate goal of increasing the integration of renewable energy. Economic analysis was closely tied to the verification approaches and built on actual decision analysis tools of the energy utilities – in particular the production cost model (PCM) of Xcel Energy in Colorado. The economic analysis found that reducing mean absolute error of solar energy forecasts could lead to over $450B in energy production savings across the United States over the next quarter century.

Figure 2: Weather Information Value Chain – Solar Power Forecasting (source: Haupt et al forthcoming)
Recommendations

Based on the prior discussion and my experience in working on valuation studies for the hydro-met community I offer the following recommendations for future economic analysis of hydro-met products and services.

- all major investments or changes in hydro-met services should undertake economics analysis to demonstrate the societal value and justification of the project;
- analysis should be built on rigorous characterization and evaluation (e.g., using the VOICE approach) of the information creation, communication, and decision making process (i.e., the Weather Information Value Chain);
- to avoid “re-inventing the wheel” with each new economic study, the community could benefit from and build on a critical review and consolidation of the existing economic literature on hydro-met services and a critical review of the use of economics in national hydro-met service policy making; and
- agencies funding studies should require that studies are reliable and valid based on economic theory and rigorous methods to ensure quality and transparency of the study.

References


UPDATING DISASTER LOSSES IN AUSTRALIA: DATA, ISSUES AND IMPLICATIONS

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The Bureau of Transport Economics 2001 report: \textit{Economic costs of natural disasters in Australia} (BTE 2001), has been the only comprehensive, national assessment of the economic impacts of disasters in Australia. Statistics and economic impact assessment methodology presented in the report have been widely used for research and policy analysis, particularly for assessing the costs and benefits of risk reduction and mitigation. This is the case even though the data and analysis are over one and a half decades old.

To update this work, a new database of losses from natural hazards was developed, and to present and analyse this data using contemporary approaches to metadata and time-series normalisation. Changes in approach have occurred within the economics of disaster risk reduction and as a result of the large literature on the economics of climate change adaptation. However, the major gaps in loss data remain similar being indirect and intangible losses, with heatwaves the most underrated hazard.
IMPROVING TROPICAL CYCLONE PREPAREDNESS: A CASE STUDY FROM SEVERE TROPICAL CYCLONE MARCIA

Vicki Heinrich

Bureau of Meteorology

Post disaster surveys in Australia and internationally show that people lack awareness of their hazard risk and under prepare for hazards. This leads negative impacts with loss of life, property damage and psychological trauma. Consequently, the effectiveness of warning messages, increasing public awareness, and motivating preparedness actions are crucial for increasing public safety. That people with high risk perception and hazard experience fail to undertake suitable preparedness actions is what Wachinger, Renn, Begg, and Kuhlicke (2013) term the “risk perception paradox”. It has been a driver of research and mitigations efforts across all hazards types.

There is limited research in an Australian context testing theoretical models of cyclone preparedness. Although risk perception is important in hazard mitigation there is contradictory evidence in the literature as to which factors are related to risk perception and preparedness. Research on risk perception and hazards shows little evidence of a direct relationship between risk perception and desirable preparation behaviours. It is likely that the risk perception preparedness relationship is mediated by several variables and influenced by context and individual differences. Risk perception has been studied extensively with many behavioural theories being developed that have also been applied to hazard preparation research.

I will discuss the findings from my psychology honours thesis. Secondary data from the community survey carried out by CQU's Population Research Laboratory after severe tropical cyclone Marcia on the 20th February 2015 was used in this study. Participants from the Rockhampton Regional Council and Livingstone Shire Council areas were surveyed by phone from 22nd and 28th June 2015. Data from 408 participants was used with structural equation modelling to test a theoretical model of preparedness behaviours. The initial model was developed from protective motivation theory (Rogers, 1975), the risk-as-feelings hypothesis (Loewenstein, Weber, Hsee, & Welch, 2001), the affect heuristic (Slovic, 2010), and the preparedness and evacuation research literature.

Roger’s protective motivation theory proposes that threat appraisal and coping appraisal combine to influence protective motivation and thereby the implementation of preparedness actions or not preparing. Threat appraisal is comprised of perceived vulnerability and perceived severity and is the degree of threat an individual feels. Coping appraisal is comprised of response efficacy, self-efficacy, and response cost, and is an individual’s belief in their ability, the value, and the cost of carrying out the risk mitigating measure. Greater levels of threat lead to increasing levels of preparedness. Bourque et al. (2013) found information seeking, knowledge, and response mediated the risk perception and preparation relationship in a model derived from protective motivation theory.

Investigations into risk perception under the psychometric paradigm lead to the discovery of the affect heuristic which was later supported by hazard research. Slovic's affect heuristic states that
how a person feels, the positive or negative affect, influences the perceived risk and perceived benefit judgments in their decisions. Similarly, Loewenstein, Weber, Hsee, and Welch proposed the risk-as-feelings hypothesis. They suggest that emotions can produce behavioural responses that diverge from cognitive evaluations of what may be the best course of action. The behaviour is then driven by the emotional reaction.
DATA AND OBSERVATIONS – FUTURE PERSPECTIVES

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Introduction

With the rapid increase in data volumes and measurement technologies, there is an increasing need to strategically consider the most relevant and appropriate data types, sources and streams for the future. It is also essential to understand how these advances can shape a composite observing network and how this can support Bureau services and WMO programmes.

Importance of data

Data underpins many tools, systems, models, products and services and is thus intrinsically linked to the quality and standard of the local, national and global information relating to the atmosphere, land and oceans. Understanding the relative importance of data points for different users is also essential in the effective management of observations networks.

Assessing the value of an observation is becoming increasingly important as we strive to optimize the cost of operating observations networks whilst improving the accuracy, timeliness, impact and value of downstream products and services. Many stakeholders are choosing to invest in their own instrumentation and are looking to agencies such as the Bureau both for guidance on procurement, network design and management as well as to ingest and visualize their data. A key aspect of working and partnering with such stakeholders is determining the role of the Bureau's core network in the provision of high value services and how our observing systems can be complemented by external networks.

Data challenges

Meteorological agencies across the globe are grappling with a host of data related issues such as data sharing, open data, big data, 'internet of things', data quality, privacy, radio frequency interference and charging policies. Evolving data requirements driven by the broad and changing range of meteorological applications also present a unique and significant challenge, with network design and planning becoming increasingly important. Due to the decreasing cost of and advances in technology and the increasing demand by customers for localized meteorological information, there is a constant call on the Bureau to develop policy and best-practice guidelines. The latter include data formats, instrumentation standards, data management and ingest requirements for external stakeholders intending to share their data with the Bureau.

Changing requirements for observations

For many users of weather observations, particularly in the short-term or 'nowcasting' timescales, there appears to be no limit to the preferred data density and frequency. As the
spatial resolution of Numerical Weather Prediction (NWP) models is refined, the requirements for observational data also changes. This means large data volumes are preferred but the challenge then becomes the visualization, synthesis and analysis of the data streams. Quality also comes into question and leads to reviews of the metadata requirements and standards associated with calibration, maintenance and communication of suitable applications of different streams of observational data.

Data generation agencies, such as the Bureau, will continue to play an important role in providing a baselined, quality network of observations. Continuous improvement through the strategic evaluation of networks and data types are periodically performed to look for opportunities for improving the observations network and ensuring it meets user requirements into the future. Common standards across observing systems are a focus of WMO programmes such as the World Meteorological Organization (WMO) Integrated Global Observing System (WIGOS).

**Delivering Data for the future**

In the new organisational structure, the Bureau has placed focus on the management, stewardship and governance of its data by creating the Data Program, led by the Chief Data Officer. The key challenges and opportunities facing the Bureau in assessing value and determining needs, as well as managing, governing and archiving data will be presented. A summary of recent work to develop a tool to assess the value of observations based on NWP model skill will also be presented.

The early stages of planning activities for the assessment of composite networks and the next steps towards WIGOS are also essential for determining the configuration of the Bureau's future observations network. The ongoing question of how to access the optimal observational data inflows from external agencies through collaboration and data sharing will also be a key element to the future network. These and other elated matters will be discussed.
STATUS AND FUTURE EVOLUTION OF THE BUREAU'S MODELLING SYSTEMS

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The Bureau uses modelling systems for a range of applications, including numerical weather prediction, short-term ocean prediction, multi-week and seasonal prediction, and, experimentally, multi-year prediction. This talk introduces the Bureau's modelling systems, overviews their status and discusses plans and options for future development. Detailed results from several of these systems will be presented elsewhere in this workshop.

Numerical weather prediction utilises the Australian Community Climate and Earth System Simulator (ACCESS) based on the Met Office Unified Model (UM). The model is configured for global (ACCESS-G), regional (ACCESS-R) and city-scale (ACCESS-C) domains. The set also includes an implementation on a relocatable domain for tropical cyclone prediction (ACCESS-TC). This set of configurations is periodically updated in releases known as ACCESS Parallel Suites (APS). The current Bureau operational suite is APS2 which came into operation 2016-17. The forecast output fields from this suite are used as input into a range of applications systems, including hydrological and oceanic prediction systems. Work on the successor suite, APS3, is well advanced, with the plan to bring this into operation during 2018-19. APS3 will for the first time at the Bureau include operational ensemble prediction for ACCESS-G and ACCESS-C. APS3 will also introduce an on-demand relocatable system, ACCESS-X, for extreme weather other than tropical cyclones. The specifics of the follow-on suite, APS4, are currently under review with a focus on alignment with forecaster needs. Options for APS4 will be discussed.

Short term ocean prediction includes global and regional prediction capability, and includes wave and storm surge prediction. Global ocean prediction capability has been developed partly under the Bluelink Project, in collaboration with CSIRO and supported by the Royal Australian Navy. Prediction of temperature, salinity and current fields to 7 days lead time is performed using the OceanMAPS system, which features a global high-resolution (0.1° lat/lon grid) ocean model based on the GFDL Modular Ocean Model (MOM) 4 code. This model is planned to be upgraded to MOM5 in 2018. Regional oceanic prediction capability has been developed as part of the eReefs project and uses the ROMS model at fine (order of 4 km and 1 km) spatial resolution. The ROMS model is also used for storm surge prediction as part of a national system run daily and a tropical cyclone system run on demand. Wave prediction is performed using the AUSWAVE model, which is based on the NOAA WAVEWATCH III code. The potential for further development of a coastal ocean prediction capability will be discussed.

Multi-week to seasonal prediction at the Bureau has previously used the POAMA prediction system, but will henceforth use the ACCESS-S system. ACCESS-S is based on the Met Office GC2 global coupled model, and has considerable enhancements compared to POAMA, including higher vertical and horizontal resolution and state-of-the-art physics parameterisation.
schemes. The initial version, ACCESS-S1, is due to become operational in early 2018. Ensemble forecasts will be generated daily, with forecasts out to 6 months lead time. A 23-year hindcast set has been completed and supports the real-time forecasts. Work on the successor ACCESS-S2 is in progress, this version includes a locally-developed data assimilation system. A subset of the ensemble forecasts using ACCESS-S2 are anticipated to be extended to 36 months lead time for experimental multi-year prediction. Planning for ACCESS-S3 and S4 is underway, and will be reviewed.
CONTRASTING WEATHER SERVICE EVOLUTIONS FOR THE DEVELOPED AND DEVELOPING WORLD – AN EXAMPLE FROM THE AUSTRALIA / PAPUA NEW GUINEA RELATIONSHIP

Andrew Tupper

Bureau of Meteorology

Meteorological services are increasingly reliant on high degrees of automation, to assist with handling large amounts of information, communicating complex ideas to multiple stakeholders, and deriving the best value from increasingly advanced numerical prediction. Within Australia, we have managed to keep up with the rapid evolution of our science and services through strong partnerships with the UK and US and others, support from the Australian government and our own hard work.

But what if the strong partnerships, core Government support, and organisational functionality were all compromised? What if we fell below critical mass in terms of resources? How do all the World's met services keep up, and how do we avoid splitting the world into haves and have nots? In the Australian region, we can consider the examples of our neighbours, from fledgling countries such as Timor-Leste, to long-established smaller countries such as Papua New Guinea and Fiji, and to sophisticated but smaller economies such as New Zealand.

As a focus example, let's look at Papua New Guinea. The Papua New Guinea National Weather Service was set up by the Bureau of Meteorology well prior to independence, with a staffing and network appropriate for the times. Following independence in 1975, the NWS has essentially operated separately from Australia and has faced considerable challenges, to the point where an Australian-PNG partnership has been established to help improve NWS services. But where should the NWS aim to be? A full GFE-style forecaster interface and supercomputing system is not realistic, but what is, and how do challenges in PNG affect the quality of forecasts in surrounding countries? How will we develop our own services in a way to help our neighbours? This talk will explore these issues and Australia's regional role of partnership with our neighbours in service delivery.
ENSEMBLE APPLICATIONS FOR HIGH-IMPACT WEATHER AT THE MET OFFICE

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Introduction

This year marked the 25th anniversary of operational ensemble forecasting at ECMWF (European Centre for Medium Range Weather Forecasts) and NCEP (US National Centers for Environmental Prediction). In the last 5 years a number of NMSs (National Met Services) including the Met Office have introduced convection-permitting ensembles, bringing the science truly into the field of short-range forecasting as well as the medium range. This investment is founded on an understanding of predictability, on good evidence that use of probabilities can support better decision-making than “traditional” deterministic forecasts and on scientific integrity of wishing to communicate the full picture of what is and isn't predictable. Yet, as a community we are still struggling to fully exploit and communicate the probabilistic information from ensemble forecasts. One of the key aims of ensemble forecasting, but also the more challenging, is to improve the prediction of high-impact weather events in support of decision-making for protection of life, prosperity and well-being. This paper will consider some of the tools developed at the Met Office to exploit ensembles and support decision-making both within and beyond the Met Office.

High-Impact Weather Prediction and Risk

Weather forecasts are only of any use when they lead to effective decision-making, whether it be for societal protection or to improve the profitability of an economic activity. In order to support decision-making, users need to understand not just what weather to expect, but also its likely or potential impact:

*Not what the weather will be, but what the weather will do.*

With this in mind, weather does not necessarily need to be extreme to have a high impact. Temperatures around 0°C are not extreme in many parts of the world, but have a high impact on road safety. Making good decisions on road management then requires an understanding of not just the air temperature, but also the road temperature, precipitation and road wetness, and the numbers and types of vehicles using the road and therefore liable to be affected by any icy conditions. This is an example of where decision-making is a matter or risk management, where risk is the combination of the probability of a hazard (weather event) with the likely impact of that event, where the impact depends on both the societal vulnerability to the hazard and the exposure representing the number of vulnerable assets:

\[ \text{Risk} = p(\text{hazard}) \times \text{Vulnerability} \times \text{Exposure} \]  

(1)
Ensemble forecasting helps provide the first component of risk, \( p(\text{hazard}) \), but effective decision-making needs to take account of the full risk equation. Meteorologists cannot usually do this in isolation, but need to work in collaboration with partners and end-users who have the knowledge of vulnerability and exposure. The final part of the decision-making process is, once we have an understanding of the risk, what protective action can be taken, and what that might cost. The cost-loss approach to decision-making originates from the work of Murphy (1977) and has been promoted by ensemble forecasters for many years (e.g. Mylne, 2002; Richardson, 2000). The full analysis of risk helps analyse the potential loss for use in a cost-loss decision process.

In practice a full analysis of risk is not always feasible and often highly specific to an application and a user. For a NMS the issue of severe weather warnings or the development of high-impact weather prediction or alerting tools is necessarily more generic for use by multiple users and decision-makers, and often focuses more on the hazard. In this paper we shall present a number of tools which analyse increasing degrees of detail in the risk equation.

**Global High-Impact Weather Diagnostics**

High-impact weather hits the world news headlines many times every year due to extreme weather events leading to disasters impacting the lives of many people. Effective mitigation of such events is a key aim of the UNISDR Sendai Framework for Disaster Risk Reduction, and effective early alerts of such large-scale events are a key tool in enabling better preparedness to prevent loss of life and enable timely deployment of relief efforts. One of the leading causes of such disasters is Tropical Cyclones (TCs) and ongoing research at the Met Office in ensemble TC tracking has demonstrated the benefits of multi-model ensemble TC forecast products, building on the work of the THORPEX project. The most recent MOGREPS-G and ECMWF resolution increases now mean the global ensembles can give useful information on TC intensity, but this has recently been enhanced by the development of a relocatable 4.4km convection-permitting ensemble capability which was demonstrated Hurricanes Irma and Jose. Early indications are that this gave more realistic storm intensities. MOGREPS-G TC forecast products are shared with the WMO TC Centres.

Another capability which will be demonstrated is a Global Hazard Map (GHM) which displays global alerts for ensemble probabilities of events exceeding the 99th percentile of local climatology with the aim of highlighting potential high-impact weather across the globe in the next 7 days. While this is essentially a hazard forecast, society and infrastructure is normally quite resilient to normal events within local climatology, but can be vulnerable to events at the extremes of climatology, so the 99th percentile provides a basic global measure of high-impact weather risk. Forecasts may also be overlaid over some basic global datasets of vulnerability and exposure, such as population density or a fragile states index, which go the first step towards making an impact assessment. GHM is used by global forecasters in the Met Office and may be shared with international partners in support of disaster risk reduction activities.

**Weather Regime Analysis for Impacts**

The Decider weather regime analysis was developed as a new method of ensemble clustering to summarize the medium-range ensemble forecast for the UK in terms of weather regimes which are recognizable and meaningful to the operational meteorologist (Neal et al 2016). It is based
on a set of 30 regimes which may also be further grouped to a set of 8 regimes mainly used for long-range forecasting. These regimes were objectively defined using a clustering of historic reanalysis data and reviewed by an operational meteorologist to ensure they capture the important flow regimes for UK forecasting. The power of regime analysis lies in the fact that meteorologists can associate regimes with certain weather types experienced on the ground in specific parts of the country. The same concept can then be applied to weather impacts, where these are strongly associated with particular flow regimes. By identifying the regimes under which a particular impact is more likely to occur, one can then work out a conditional probability of that impact given a regime, based on historic records; combined with the ensemble probability of that regime occurring, this provides an approach to probabilistic impact prediction. This approach has been applied in several areas: coastal flooding, pluvial flooding and the risk of disruption to aviation in W. Europe in the event of a volcanic eruption in Iceland.

This approach is illustrated here by the example of *Coastal Decider* in which historic coastal flooding events due to a combination of storm surge and large waves have been associated with 5 or 6 out of 30 regimes, depending on which part of the coast is at risk. Combining this information with ensemble regime probabilities (fig 1a) and information on spring tides provides an early alert to enhanced risk of coastal flooding based on medium or long-range forecasts (fig 1b).

**EPS-W – Ensemble Prediction System first-guess warnings**

The UK National Severe Weather Warning Service (NSWWS) is an impact-based warning system which issues colour-coded warnings (Yellow, Amber, Red) according to a risk matrix (Fig 2) taking account of the likelihood and potential impact of the expected weather. A similar consistent approach is also used for flood warnings issued in England by the Environment Agency. NSWWS impact assessments are largely subjective by operational meteorologists based on their knowledge of societal vulnerability, developed in consultation with civil responder organisations who are the primary customers for NSWWS. EPS-W was developed as a tool to aid the operational meteorologists in issuing NSWWS warnings by providing a first-guess warning colour based on ensemble probabilities (fig 3). For the impact axis of the matrix, EPS-W uses a set of impact-based thresholds for strong winds, heavy rainfall, snowfall and visibility. These impact-based thresholds vary geographically and seasonally across the UK according to societal vulnerability and exposure which depends on a combination of local climatology and population density. For example, strong winds are far more common in NW Scotland than in SE England so the windspeed threshold for a high-impact warning is much higher in NW Scotland both because infrastructure is better prepared and built for strong winds (due to climatology) and the exposure is less because of lower population density. Using these thresholds, EPS-W scans the forecast fields from ensembles and estimates the probabilities for each impact category in the matrix, and then selects the colour from the highest-numbered box in the matrix (fig 2).

EPS-W is currently implemented for the MOGREPS-G and ECMWF global ensembles, and with the Met Office’s 2.2km convection-permitting ensemble, MOGREPS-UK. For severe weather, one of the challenges is whether the models used in the ensembles are able to fully represent the intensity of hazards associated with high impacts. By use of impact-based thresholds there is an opportunity to tune the thresholds to allow for model capability, and the
global ensemble thresholds are currently set at 75% of the impact thresholds for precipitation impacts (rain and snow) established in consultation with users. In general the convection-permitting ensembles would be expected to provide a better representation of the intensity of weather associated with high-impact weather, needing less calibration of this type. In practice this is not yet the case for wind warnings using MOGREPS-UK, due to the difficulty of reliably representing wind gusts in convection-permitting models (Mylne and Roberts, 2017), and currently MOGREPS-UK based EPS-W warnings tend to underestimate strong winds with the global ensembles providing better guidance. EPS-W is fully described by Neal et al (2014).

Hazard Impact Model

The Hazard Impact Model (HIM) concept has been developed collaboratively within the UK Natural Hazards Partnership to fully estimate the risk model in equation (1). HIM modules have been developed for the impact of wind causing disruption on the road network through large vehicles being blown over and for Surface Water Flooding due to heavy rain. The HIMs exploit the high resolution detail of weather hazards from the short-range convection-permitting ensemble MOGREPS-UK and project it onto geospatial information on vulnerability and exposure of potential receptors to produce detailed mapping of expected risk. This will be illustrated particularly through the example of the Vehicle Over-turning Model.

**Fig 1a:** Ensemble clustering by weather regime. The shading and number of ensemble members of each regime in the table indicates its relative probability on each day of the forecast.

**Fig 1b:** Coastal Decider forecast indicating flood risk on coasts. Yellow/amber shading indicates enhanced risk due to spring tides.
Fig 2: Impact-based risk matrix used in the NSWWS. Note that the numerical values for likelihoods are specific to the first-guess EPS-W; the NSWWS uses only the word descriptions of likelihood.

Fig 3: Example 2-day first-guess wind warning from EPS-W based on the MOGREPS-G global ensemble for ex-hurricane Ophelia on 16 October 2017.

References


STATISTICAL POST-PROCESSING OF ENSEMBLE NUMERICAL WEATHER PREDICTION GUIDANCE

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Introduction

Much of the medium-range guidance post-processing (GPP) at the Bureau of Meteorology in recent years has been focused on providing guidance that is good enough to allow greater automation of weather forecast production in routine (roughly, non-warning) conditions. The focus of GPP has mainly been on improving daily rainfall and coastal daily maximum / minimum temperature guidance, as these have consistently been seen as the biggest blockers to greater automation.

Hence in this abstract, we focus on improvements to daily rainfall and temperature guidance based on a Gridded Operational Consensus Forecasts (GOCF) system (Engel and Ebert 2012). We briefly touch on spatial downscaling and opportunities for expanded machine learning. Finally, we look to the future of GPP.

New calibrated ensemble daily rainfall guidance

The most important general weather forecasts for the public and forecasters alike are consistently found to be for rainfall. Calibrated, combined and downscaled (i.e. post-processed) guidance from Numerical Weather Prediction (NWP) is found, on average, to out-perform raw NWP for medium-range weather forecasting (e.g. Novak et al, 2014). Post-processing also acts as an abstraction layer (a sensible filter) to an ever growing mountain of data which will become increasingly difficult for humans to process without GPP, and automation and presentation support.

A new daily ensemble rainfall probability GPP system is discussed here. Both “Poor Man's Ensembles” (PMEs) of local and international deterministic guidance, and the native European Centre for Medium Range Weather Forecasting (ECMWF) global weather forecast ensemble (ECEPS) are used as inputs. The inputs are combined in probability space in a process analogous to quantile mapping.

The ECEPS and PME forecast rainfall amounts and probabilities are averaged with relative weights determined by the number of members in each ensemble and some optimisation from re-forecast verification. Probabilities from the combined forecast are produced both by using the uncalibrated 'voting' probabilities from ensemble member counting and calibrated Bayesian probability density functions. The latter are empirical functions of the ensemble mean and the 'voting' probabilities, fitted to training data. The calibration maximises skill in re-forecasts over a year. Calibration categories are used which take into account the reliability of rain / no rain guidance and rainfall amount guidance; this provides a degree of localisation of calibration.
Further explicit localisation is being explored. The 'truth' data for calibration and gridded verification are Australian Water Availability Project analyses (Jones et al., 2009) close to rain gauges.

These approaches have increased daily rainfall probability guidance skill by the equivalent of about 36h lead time over the last 2 years, averaged over Australia, of which about 24h is due to the merging of PME and ECEPS guidance (Figure 1).

![Brier Skill Score relative to verification data climatology](image)

**Figure 1:** Brier Skill Scores of GOCF daily rainfall exceedance probabilities using ECMWF EPS (solid line) vs operational (dotted line) forecasts not using the EPS. The reference forecast probabilities are the rain frequencies observed in the 0.25 degree resolution verification data sample.

A further 12h lead time has been gained for 00 and 12Z-based guidance by minor re-scheduling that lets the most recent global models be used. Further significant skill gains in official forecasts are expected from a combination of GPP improvements, the ACCESS-GE3 ensemble and changes to business rules currently encouraging forecasters to bias probability forecasts. Situation-dependent climatological downscaling of rainfall will be explored.

The most recent guidance, not yet routinely available to forecasters, has become more skillful than the majority of official forecasts on average as measured by Brier skill score at rain gauges. However, official forecasts may still be competitive with guidance over some northern and coastal eastern areas, principally in summer (Griffiths et al., 2017) and all medium-range guidance and forecasts suffer lack of resolution and / or accuracy over elevated terrain in some conditions. Further developments are expected to address any such issues.
New daily temperature guidance

Bureau of Meteorology maximum and minimum temperature forecasts (max / min T) have a dual nature – site forecasts where observations are available and 3 to 6 km grid box averages elsewhere. These are informed by site guidance tuned against observations, and gridded guidance tuned against 2.5’ resolution Mesoscale Surface Analysis System (MSAS) (Glowacki et al, 2012) analyses. As no MSAS max / min T analyses are available, the max / min of hourly analyses are used as proxies for tuning the max / min of hourly gridded guidance to estimate daily max / min T. For spatial and temporal sampling reasons, this biases the estimated gridded max / min T guidance compared to daily max / min T observations.

Currently, gridded guidance is modified to match co-located site guidance. These modifications, which can exceed 10 °C, are interpolated in space to other grid points. However, the modification between gridded (area) and site guidance is often unrepresentative of surrounding locations, particularly near the coast. Hence the interpolation of modifications can produce up to 10 °C max / min T errors between observation sites. Forecasters must check and fix those temperatures before they are published.

To address these issues, many steps are being taken to reduce discrepancies between site and gridded guidance. The production of direct (rather than estimated) gridded max / min T guidance is key, so that site guidance can just replace gridded guidance at sites and modifications to the gridded guidance elsewhere are not needed. Direct max / min T guidance is based on a bias-correction of hourly MSAS analyses to produce daily max / min T analyses.

As the impacts mostly occur between observation sites where we have no independent max / min T analysis for verification, a cross-validation has been performed to help demonstrate improvements to forecast skill.

When is the guidance good enough?

A separate activity is looking into what level of guidance quality is good enough to enable automation in routine conditions. That helps to define what can be automated and where to focus development effort.

Downscaling, situation-dependent calibration and machine learning

Global guidance typically has resolved spatial scales of tens of km, whereas we are currently preparing public forecasts on 3 to 6 km grids. Further, the spatial scale of GOCF daily rainfall guidance is around 0.25 degrees, and the spatial smoothing of NWP topography reportedly contributes to some global NWP topographically-driven precipitation occurring upstream of reality, and not having the topographic resolution (particularly from global ensembles) to pick up higher rainfall on some of the topography.

Calibration of NWP rainfall guidance, while generally found to be successful, suffers from the temporally and spatially-isolated nature of rainfall. That in turn means long training sets and spatial aggregation of training data are required for robust calibration. However, situation-dependent downscaling of rainfall based on climatology avoids some of the data issues, and some work in the South Australian Regional Office suggests such downscaling may be a viable
approach. Downscaling of rainfall probabilities is more difficult but should be viable if downscaling rainfall amount is viable.

More generally, GOCF for fields other than rainfall has mostly used simple bias correction in order to keep training periods short and hence rapidly adapt to changes in NWP – given we have found use of many-predictor model output statistics (MOS) to be problematic when deterministic NWP guidance changes without NWP reforecasts. However, it is likely that better guidance can be obtained by introducing up to a few additional predictors, supported if necessary by increasing the size of training sets by spatial aggregation of like data, such as by DWD using Ensemble Model Output Statistics (EMOS) (Hess et al., 2015), and as has been used with GOCF rainfall and by Hamill et al. (2017). Another example of using multiple predictors using analogue and other statistics is Eckel and Monache (2016).

In general, these approaches require predictor selection and weighting, such as by traditional machine learning in meteorology over the last few decades. However, recent advances in software libraries to support neural-network-based image processing may aid further advances in this space. We are trialing downscaling of temperatures near the coast using such an approach. We currently downscale temperature using a statistical approach on recent data.

**Looking ahead**

Convection Allowing Models (CAMs) and ensembles provide a step-change in the capabilities of NWP in some areas – for example, better-located and better-timed rainfall with improved statistical properties. There is extensive anecdotal evidence that CAMs have skill at forecasting the mode of thunderstorms; however the location of those and other features in a CAM often remains unforecastable, so ensemble-based CAM output and post-processing is required to provide appropriately-neighborhood-smoothed probabilities of occurrence / exceedance. Analogous post-processing is required to take full advantage of rapid update cycle guidance and CAMs. Nowcasting such as from STEPS (Bowler et al., 2007) will increasingly use Rapid Update Cycle and CAM ensembles.

At all time ranges, there is a growing need for calibrated seamless probability, scenario and risk forecasts of basic weather parameters and derived impacts based on ensembles – such as probabilistic fire danger indices, thunderstorm forecasting, energy supply and demand, smoke / chemical dispersion, tropical cyclone impacts and heatwaves. Such forecasts in turn support decision-making by our users, including around extreme events. They will also support our forecasters in high impact situations, including by providing valuable intelligence and reducing editing workload. Commercial international weather providers such as IBM / the Weather Company are aggressively moving into such spaces. While we have made good starts with GPP, we are investigating further collaborations to pool resources in these spaces.

**References**


Engel, C. and Ebert, E.E. 2012: Gridded Operational Consensus Forecasts of 2-m Temperature over Australia, Weather and Forecasting, 27, 301-322.


WEATHER FORECAST PROCESS STREAMLINING AND EVALUATION

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Existing weather forecast value chain

The Australian Bureau of Meteorology’s 7-day public weather forecast services can be considered as part of a value chain in which the worth of meteorological information is progressively increased to maximize the benefit which is realized by the end user, as outlined in Figure 1. These services include text forecasts and warnings, graphical displays via web and apps, and the Australian Digital Forecast Database (ADFD) containing 6 km resolution gridded forecasts of the sensible weather elements which underpin many of the other services.

Gridded forecasts, graphics and text forecasts are generated by the Graphical Forecast Editor (GFE) software. The GFE was initially developed by the US National Weather Service (Glahn and Ruth, 2003) and was extensively modified for use in Australia. The GFE provides a mix of manual and automated processes. Forecasters can make choices about what guidance to use as the starting point for the forecast and utilize a variety of grid editing tools to adjust the forecast grids. Some tools automate a number of steps following broad process choices made by the forecaster. These tools can edit multiple grids over multiple days at once and derive weather elements such as fire danger indices which are not present in the incoming guidance. The forecaster then runs GFE natural language generation software which drafts the text components of forecast and warning products based on the grids. The text can be edited by forecasters before the products are issued.
The guidance supplied to the GFE as the starting point for the forecast includes the Operational Consensus Forecast (OCF) poor-man’s-ensemble of Numerical Weather Prediction (NWP) models (Riley et al., 2016). A small number of single NWP outputs from the Australian ACCESS suite, ECMWF and the US GFS models are also available for forecasters to use directly in the GFE.

Motivation for change

The GFE brought a large expansion in the Bureau’s forecast services out to 7 days ahead for a 6 km grid across Australia. The intention was to produce a vastly increased service, rather than to reduce the number of forecasting staff. In some offices, an increase in staffing was in fact required to handle the GFE workload.

With increasing pressure on the Bureau’s resource levels, there is now additional emphasis on making the most effective use of our specialist operational meteorologists. For example, it is being questioned whether an hour spent editing gridded forecasts for lead day 7 (i.e. the 7th day after today) is a better use of time than an hour spent providing decision support to a specialist user, engaging with social media about the weather story of the day, or monitoring and responding to a high impact forecast event unfolding in the next few hours. Furthermore, gridded forecasts are generated in 7 different offices with a significant degree of manual intervention and interpretation and locally inconsistent forecast processes leading to border discontinuities in the grids that can affect the credibility of the Bureau’s services.

Given these considerations, the Bureau is keen to see how the forecast production service can be further streamlined with more automated processes. Manual intervention would be limited to weather situations which are significant and in which it is reasonable to believe that a forecaster can improve on the automated forecast.

Measuring value added by the forecaster

An important consideration here is where the meteorologist best adds value in the value chain. Although it was recognized that one advantage of moving to a grid-based forecast system was that it would make objective verification of forecasts more tractable, the GFE rollout in Australia has so far been unable to capitalize on this aspect of the forecast process. We have set out to build the tools and gather the data to verify the manually edited forecasts and compare them with automated forecast sources. Our focus is on the gridded datasets produced by the GFE forecast process, noting that it is much less clear how one would objectively verify the quality of the text forecasts.

Methodology

We have gathered an archive of gridded forecasts from the GFE as well as the guidance inputs to the system from 2015 to the present, enabling us to compare the public forecasts that were issued by Bureau forecasters (‘official’) with automated forecasts which could have been constructed with the same inputs. This has also allowed us to compare the quality of different candidate automated processes so that we can improve automation tools in the GFE. The verification we have done so far has been in comparison with site observations, in part because
forecasters do not trust the representativeness of the available gridded analyses. We have made a database of forecast values together with the corresponding observations, and a set of python-language based verification tools (known as ‘Jive’) which enable us to perform analysis on the data and display results through browser-based Jupyter notebooks and dashboards. Discussions with interested parties in the Bureau have shaped the questions we have attempted to answer through verification.

We started our verification work looking at the gridded precipitation probability forecasts produced by the Bureau (Griffiths et al., 2017). We compared official forecast grids to OCF guidance for daily probability of exceeding various thresholds of rain over a number of seasons, using the Brier Score (Wilks, 2011) as a measure of skill. The comparison has been expressed both in terms of the difference in skill relative to the average increase of forecast skill with decreasing lead day (‘lead days of skill’ shown below) and as the likelihood of one source being more skilful than the other (not shown here). Verification was based on results aggregated over seasonal timescales for a variety of groupings of similar stations.

**Precipitation findings**

The verification results for daily probability of exceeding low thresholds of rain (0.2 and 1 mm) suggest that for much of the country, automated guidance already performs well compared to the official forecasts. The results in
Table 1, splitting all Australian sites into 4 groups (Figure 2), for one summer and one winter, are consistent with the overall finding that there is broadly similar performance between official and automated forecasts. Official forecasts did better in the tropics and on the east coast and ranges in summer, while automated guidance did better in southern Australia, particularly during winter.

Figure 2. Station groupings for verification results presented here.
For higher rainfall thresholds, the automated guidance also performs well in comparison with official forecasts. For example, while official forecasts performed better for the 1 mm threshold for the East Coast and Ranges stations at lead day 3 during Summer 2016/2017, the automated guidance was the more valuable for thresholds of 10 mm and greater in a day. This can be seen via calculation of Relative Economic Value (Zhu et al. 2002). In Figure 3, the Relative Economic Value curve shows more value for all user sensitivities (cost/loss ratios) for the probability of at least 25 mm of rain.

Figure 3. Relative Economic Value (REV) of official forecasts and OCF, where 1 is the value of a perfect forecast and 0 is the value of a climatological forecast. This is for probability of at least 25 mm in a day, averaged over the East Coast and Ranges stations for Summer 2016/2017 at lead day 3. The calculation assumes decisions are taken based on whether or not the forecast probability exceeds the cost/loss ratio.

**Achieving change**

The route to more automation of the GFE forecast process has been slow to navigate. We have gathered objective evidence about the value of the gridded forecasts of precipitation and will shortly be extending this to temperature and wind. We know that in some places or seasons we may lose quality with the move to more automation while in others we may gain. However, even if quality as measured by forecast verification were to drop, that may not matter as long as the quality achieved is judged as sufficient by the people using our services. Furthermore, any
drop may be offset by more value added by forecasters at the interpretation stage of the value chain. We lack a quantitative understanding of the ultimate value of our forecasts to real users, which makes it hard to set user based criteria for such standards.

There are limitations to the conclusions we can draw from our verification. The verification tells us about past forecast performance using past guidance. Guidance will change in the future (for instance there are upgrades to the OCF temperature and rainfall guidance expected in 2018) which will further improve the value of automated guidance and is likely to reduce the forecaster’s ability to add value to the guidance, particularly in the longer lead times and in more average weather patterns. If quality of automated text forecasts is a factor in decisions regarding automation, then this will involve weighing subjective opinions.

The Bureau’s NSW State Office pioneered the use of an automated process for their lead day 5 to 7 forecasts over the last 4 years, and this service has proven acceptable to the community. A measure of the quality that has been accepted for automation for our most populous state could be used as a national benchmark for acceptable performance.

The Bureau aspires to achieve national automation of the GFE forecast process, at least for lead day 5 to 7 forecasts in most situations, during the course of 2018. Our objective verification will ensure that when decisions are made to automate, we will better understand the implications this has for our forecasting service, and will appreciate where meteorologists are best placed to contribute to the value chain.

References


GENERATING SPATIO-TEMPORAL PRECIPITATION FORECAST FIELDS BASED ON THE OUTPUT OF THE GLOBAL ENSEMBLE FORECAST SYSTEM (GEFS)

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**Introduction**

Hydrological forecasts strongly rely on predictions of precipitation amounts as meteorological inputs to hydrological models. Ensemble weather predictions provide a number of different scenarios that reflect the uncertainty about these meteorological inputs, but often require statistical post-processing to remove biases and adjust the spread. In hydrological applications, it is crucial that correlations in space and between different forecast lead times are adequately represented by the recalibrated forecasts, and this requires additional modeling efforts.

**Multivariate postprocessing of GEFS forecasts fields**

We present a study with precipitation forecasts over a rectangular domain covering the Russian River Watershed in California. Numerical weather predictions from the Global Ensemble Forecast System (GEFS) are statistically post-processed with the censored, shifted gamma distribution method by Scheuerer and Hamill (2015), using climatology-calibrated precipitation analyses as the ground truth. For modelling spatial and temporal dependence we follow Scheuerer et al. (2017) who propose a variant of the Schaake Shuffle (Clark et al., 2005) that uses spatio-temporal trajectories of analyzed precipitation as a dependence template, and chooses the historic dates in such a way that the divergence between the marginal distributions of these trajectories and the univariate forecast distributions is minimized. In the setting discussed here, however, the selected historic analyzed trajectories are not only used for modelling spatio-temporal correlations between the precipitation amounts at the GEFS grid scale, but also serve as templates for disaggregating precipitation amounts to the high-resolution analysis grid. This procedure allows one to generate space-time forecast fields of precipitation that are both reliable and physically realistic, and can be used for example as meteorological inputs to a distributed hydrological forecast system.

**References**


HIGH RESOLUTION DATA ASSIMILATION IN ACCESS

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Introduction

The Bureau of Meteorology’s next generation high resolution Numerical Weather Prediction (NWP) system will include data assimilation. The third generation of the City (or state) based NWP systems use the latest version of the Australian Community Climate and Earth System Simulator (ACCESS-C; C for City). While the Bureau currently has convection-permitting systems running operationally (ACCESS-C2), they only downscale lower resolution NWP models. The enhanced resolution of these downscaling convection-permitting systems has been shown to provide a much more realistic depiction of the small scale features and topographic forcing. One of the most important gains is the ability to explicitly represent storm scale phenomena, leading to a greatly improved depiction of the life-cycle of large convective systems.

One of the key new aspects of the ACCESS-C3 systems is the introduction of data assimilation. This has several benefits, firstly, the initial conditions inherently have the small scales initialized, unlike those derived form a coarser grid model. Secondly this also allows for a more frequent updating of the forecast as the model is no longer dependent on a large scale global or regional model for initial conditions, giving users more frequently updated and more accurate predictions of storms, wind changes and other short-lived weather events. Thirdly, the high resolution of the convective scale systems means that in addition to the observations assimilated into larger scale NWP systems, a range of new observations will be used to further improve the initial conditions.

The ACCESS-C3 systems

There are six convective-scale NWP systems, focused on the capital city areas and covering most of the Australian population. The six ACCESS-C3 domains are shown in Figure 1. The domains are referred to as Perth (PH), Darwin (DN), Brisbane (BN), Sydney (SY), Victoria/Tasmania (VT) and Adelaide (AD). Each domain has a variable grid, where the core is fixed at 0.0135° (about 1.5 km), bounded by short region of stretching, outside which the grid is 0.036° (4 km). The domains will be nested in the coming 12 km resolution Global system (ACCESS-G3), or the current operational Regional 12 km resolution system (ACCESS-R2) for trialling.
The ACCESS-C3 suite contains the series of tasks required to produce a forecast. Each cycle of the suite contains tasks to retrieve and process observations, conduct the data assimilation, run the forecast with the updated initial conditions, and archive the output. The forecast provides the ‘background’ for the subsequent cycle, i.e. the first guess for the initial conditions. The background is also used in observation processing for quality control, and in the data assimilation step. Since the model is capable of capturing small scale phenomena, the error of representation of observations is reduced, and hence observations can be fitted more closely.

ACCESS-C is being trialled with suites that cycle hourly or 3-hourly, with long forecasts produced at 00Z, 06Z, 12Z and 18Z. The intervening short forecasts are primarily to provide the background for the next cycle.

Figure 4. The ACCESS-C3 domains with inner 1.5km area in delineated red, outer limit of variable grid in blue.

**Observations**

ACCESS-C assimilates a range of conventional and satellite observations, some of which have not been assimilated before in ACCESS. The observation types assimilated (or under development) are shown in Table 1.
Table 1. List of observation types to be trialled in ACCESS-C3. Observation types in italics include new observations not assimilated previously.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Satellite radiances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiosondes and wind profiles</td>
<td>Satellite wind Atmospheric Motion Vectors</td>
</tr>
<tr>
<td><strong>Doppler radar radial velocity</strong></td>
<td>Satellite scatterometer winds</td>
</tr>
<tr>
<td>Aircraft observations</td>
<td><strong>Cloud top pressure</strong></td>
</tr>
</tbody>
</table>

ACCESS-C has much higher spatial resolution and a shorter assimilation window than other ACCESS systems with assimilation. This means that observations with high spatial and temporal resolution are better utilised, or able to be assimilated for the first time.

- Surface observations from automatic weather stations at 10 minute intervals will be used.
- Doppler radar observations have very dense spatial resolution along the radial dimension. Doppler radar winds provide observations mostly between 1 km and 7 km altitude, in regions where there is precipitation to provide a radar echo. The Australian Doppler radar network has grown in recent years and most domains contain multiple Doppler radars.
- The new Himawari-8 satellite scans every 10 minutes with resolution of a few km, providing a range of products including cloud drift winds, radiances, cloud top pressures.

The assimilation of these observations with higher space/time resolution enables a much more accurate initialization of small scale phenomena.

**Data assimilation**

There are several different variational data assimilation methods being explored for ACCESS-C3. Some are more easily implemented, and so the method used is expected to evolve.

A first consideration is hourly cycling versus 3-hourly cycling. Hourly cycling has the advantage of rapid updates to the initial conditions. However, its disadvantage is that observations that are not received within a short time after they are taken will not be available for assimilation. This can mean that many observations are excluded. An additional option is a late cut-off assimilation run, which has the same analysis time as a previous forecast, but is run at a later time to allow more observations to be included. This late run only involves a very short forecast which produces the background fields for the next cycle, rather than a long forecast.

There are several assimilation schemes that will be trialled.

- 3D-Var uses a 3-dimensional optimisation to minimise the difference between the observations and the background. 3D-Var is cheap to run, however it cannot use
information related to the temporal evolution of observations during a given assimilation window.

- 4D-Var uses a 4-dimensional optimisation, and so can account for the temporal evolution of observations. 4D-Var is more expensive to run as it requires running a simplified atmospheric model multiple times over the assimilation window. Standard 4D-Var however starts from static background error covariances, which limits the relationship between the spread of information from observations and actual forecast error.

- Hybrid 4D-Var uses information from ensemble forecasts to provide information about the model background error. A more accurate estimate of the model background error means that the spread of information from observing sites can be spread in manner that better reflects the forecast error at that particular time. However, this requires an ensemble to run. ACCESS-C3 will have an ensemble (CE3) system, but the number of ensemble members may not be sufficiently large to accurately estimate the error. Therefore this type of assimilation will be tested but may not be suitable in the immediate future.

The initial trials for ACCESS-C3 have used 3-hourly 3D-Var. New trials are being run with hourly 4D-Var. There are plans to compare different windows and assimilation schemes to determine the best choice for ACCESS-C.

**Summary**

The introduction of convective-scale NWP with ACCESS-C2 has provided large improvements in the forecast of intense storms and orographically-driven mesoscale weather. ACCESS-C3 is the Bureau’s first convective-scale NWP system with data assimilation, which can provide frequent forecasts with enhanced initial conditions. A range of observations will be assimilated at higher spatial and temporal resolutions than previously possible, including radar wind observations, 10-minute synoptic observations and new satellite observations. Several different data assimilation choices are being explored but it is anticipated that 4D-Var will be the main focus of development in the immediate future. The rapid update cycle is expected to provide forecasts more often, for better guidance especially during severe weather events.
UM PHYSICS DEVELOPMENTS FOR IMPROVED CONVECTIVE-SCALE FORECASTS

Charmaine Franklin

Bureau of Meteorology

Introduction

This presentation will cover some of the latest UM developments from the UK Met Office that will be included in C3/CE3. The developments that will be described include:

1. Moisture conservation
2. Climatological aerosols, cloud droplet number concentrations and indirect effects
3. Blended turbulence scheme
4. Scale-aware warm rain microphysics
5. Stochastic boundary layer perturbations

1. Moisture conservation

When explicitly representing convection in the UM/ACCESS, the model produces excessive precipitation. This problem is worse in the tropics where convection is more intense but is also noticeable in the midlatitudes. Although the representation of convection is sensitive to the resolution, the conservation errors associated with the semi-Lagrangian advection scheme have been found to account for a large amount of spurious precipitation. To address this problem, a moisture conservation scheme has been developed that restores the correct amount of mass. This leads to a reduction in the overestimate of precipitation and maximum rain rates, which should help to improve forecasts of heavy rain and flooding.

2. Climatological aerosols, cloud droplet number concentration and indirect effects

Climatological aerosol concentrations will be used in C3/CE3 to derive the cloud droplet number concentration. From the droplet concentration the effective radius of cloud droplets is calculated within the microphysics scheme for the 2nd indirect aerosol effect (precipitation efficiency). This effective radius is also used by the radiation scheme for the 1st indirect effect (cloud albedo), where in the past the cloud droplets seen by the radiation scheme assumed a fixed size for long-wave radiation and a fixed number concentration (with a land-sea split) for short-wave calculations. This means that the model now has a consistent representation of the 1st and 2nd indirect aerosol effects, which improves cloud and screen temperature errors in the UK.

3. Blended turbulence scheme

Two different types of turbulence schemes exist for use in atmospheric models: a 1D scheme designed for coarser resolution models with horizontal grid length > about 4km, and a 3D scheme for high resolution models with horizontal grid lengths < 100m. When the model
resolution is in the turbulence grey zone between these resolutions, this raises the question of what is the most appropriate scheme to use. The Met Office have developed a blended turbulence parameterisation scheme where the turbulent mixing is defined to be a weighted combination of the one-dimensional planetary boundary layer scheme and a three-dimensional Smagorinsky sub-grid turbulence parameterisation, with a weighting that depends on the ratio of eddy size to grid length. This scale-aware scheme has been shown to improve the spurious break-up of stratocumulus that was caused by errors in the representation of turbulent eddies, improving cloud and temperature forecasts.

4. Scale-aware warm rain microphysics

Cloud microphysical parameterisations typically take grid box mean values of cloud and rain water contents as inputs, however, the processes that these parameterisations represent take place on a much smaller scale than the grid box. Averaging these process rates up to the grid box scale often leads to incorrect rates as the processes are generally nonlinear. A parameterisation for the sub-grid variability of cloud and rainwater content has been developed that is applicable for all model grid lengths. This sub-grid parameterisation is used to calculate the cloud microphysical process rates and improves the forecasts particularly of light rain.

5. Stochastic boundary layer perturbations

While implementation of the blended turbulence scheme significantly improves the simulation of stratocumulus clouds, the scheme can delay the initiation of convection in the model. To deal with this, stochastic perturbations are added to the potential temperature and moisture fields in the lower part of the boundary layer in convectively unstable regimes. The magnitude of the perturbations is small and scales with the sub-grid surface fluxes such that the larger the heat flux, the larger the stochastic forcing. As well as helping to initiate and develop small-scale convection, these stochastic perturbations help with spinning up convection along the lateral inflow boundaries of the model domain.
**BOM ATMOSPHERIC HIGH-RESOLUTION REGIONAL REANALYSIS FOR AUSTRALIA (BARRA): STATUS AND PROGRESS**

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**Introduction**

Reanalysis is a consistent reprocessing of archived weather observations from multiple sources using models to interpret, relate and combine them (Dee et al., 2014). This generates a comprehensive and physically consistent reproduction of the atmospheric circulation that matches the observations closely. There are several completed global atmospheric reanalysis products covering the Australian region (see [http://reanalyses.org](http://reanalyses.org)), such as NCEP’s Climate Forecast System Reanalysis (CFSR) and ECMWF’s ERA-Interim, but they are provided at spatial resolutions coarser than 50 km; the new ECMWF ERA5 reanalysis has 31 km resolution. Reanalyses at higher resolution will benefit climate services and atmospheric science research conducted at local scales (1 km to 10 km).

The Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) – the first of its kind for Australia – aims to support high-quality assessments of environmental risk and likelihood of extreme events (Jakob et al., 2017). The Bureau is making a major investment to develop this new dataset because of the important benefits it offers to Australia. This investment is supported by fire and environmental agencies in various States in Australia because the reanalysis data can enable a greater understanding of past fire weather and other extreme events.

The Bureau is constructing a 25-year (from 1990) high-resolution atmospheric reanalysis based on its numerical weather forecasting model ACCESS (Australian Community Climate and Earth-System Simulator) (BoM, 2013). The reanalysis comprises a 6-hourly assimilation system based on the Uncertainties in Ensembles of Regional ReAnalysis (UERRA) system used at the UK Met Office (UERRA, Jermey & Renshaw, 2016) – although without the ensemble component. Figure 1 shows the region covered by the reanalysis. We use observations from weather stations, aircrafts, radiosondes, ships, buoys, and various satellites. In particular, we utilise high resolution local surface observations (over Australia and New Zealand), and locally produced satellite-retrieved wind vectors that are not available for the coarser global products. By using a higher resolution model, more observations can be used to add valuable information at finer scales.
Development of regional reanalysis

The BARRA reanalysis is being produced in two steps. The first step delivers a reanalysis over the Australian domain at (approximately) 12-km resolution (BARRA-R). This is by far the more computationally demanding step as the observations are combined with the model physics via data assimilation using 4D variational assimilation scheme for the atmosphere and an extended Kalman filter for the land surface. The lateral boundary conditions are from the ERA-Interim 80 km reanalysis. The soil temperature and moisture fields are derived from a lower resolution (60 km) run of the Joint UK Land Environment Simulator (JULES), forced by ERA-Interim atmospheric variables. In the second step, we use a dynamic atmospheric model to downscale the BARRA-R reanalysis to a 1.5-km resolution, up to 40 km into the atmosphere for a small number of subdomains (Figure 1). Downscaling for some of these subdomains is in production while others are in development and more subdomains may be added at a later time.

BARRA-R and the subsequent downscalers produce about 100 parameters at hourly (and some at 10-minute) time intervals. The following gives a flavour of what the reanalysis will provide: information about surface conditions (such as temperature, precipitation, wind vector, humidity, evaporation and soil moisture), information at 37 pressure levels and 70 model levels, and information on solar radiation and cloud cover. Production is on track to complete the first six years (2010 to 2015) of reanalysis data for BARRA-R, BARRA-SY and BARRA-TA in late 2017. Further releases of six-year blocks of data are planned at roughly six monthly intervals.

Evaluation of BARRA

Our evaluation results for BARRA-R include a comparison against observed screen-level temperature, dewpoint and surface pressure, and wind speed at 10m height (Figure 2) against up to 1200 surface stations. BARRA-R is found to be more skillful than ERA-Interim in terms of Root Mean Square Error (RMSE) (and bias, not shown). This result illustrates the importance of increasing spatial resolution from 80 km to 12 km and assimilating observations at a finer
resolution to better reflect surface conditions, validating the necessity to undertake higher resolution reanalyses. In other words, BARRA-R provides better initial conditions for the 1.5-km downscaling suite, than ERA-Interim.

Figure 2. RMSE between reanalysis and observed 2 m temperature, dewpoint, surface pressure and 10m wind speed at 06Z and 18Z across the BARRA-R domain (Figure 1). 30-day moving window averages of the statistic are shown. The notation for the x-axis is month/year (mm/yy).

Figure 3 shows the evaluation of BARRA against about 120 surface stations in the BARRA-SY domain (Figure 1). The downscaled reanalysis from BARRA-SY improves upon the skills of BARRA-R. The spatial representations for screen temperature and 10 m wind speed are more realistic with their biases relative to surface observations reduced and their spatial correlations increased.

Summary

BARRA will ultimately deliver a suite of multi-decadal high-resolution gridded meteorological datasets and as such will prove valuable for a large range of applications such as developing climatologies of weather extremes across the nation, understanding short-lived and fast-developing phenomena and the study of bushfires. Some of the benefits of BARRA in exploring weather and climate over Australia are already being realised but there is a wide scope of areas and ideas that remain to be explored.
Acknowledgements

We gratefully acknowledge the support and funding from the following agencies: NSW Rural Fire Service, West Australian Department of Fire and Emergency Services, South Australian Country Fire Service and the Government of South Australia Department of Environment, Water and Natural Resources, the ACE CRC, the University of Tasmania and the Tasmanian Government. Funding to undertake the work for Tasmania has been provided under the Tasmanian Bushfire Mitigation Grants Program. We are continuing to work with these agencies to analyse weather during and leading up to historical extreme events. We would also like to acknowledge support from many colleagues in the Earth System Modelling group at the Bureau of Meteorology.

Figure 3. Bias (top row) and correlation (bottom row) between reanalysis and observed 2 m temperature and 10 m wind speed at 06Z and 18Z across the BARRA-R and BARRA-SY domains (Figure 1) compared with ERA-Interim for the period February to September 2012. 30-day moving window averages of the statistic are shown. The notation for the x-axis is month/year (mm/yy).

References


ACCESS-TC3: DEVELOPING A NEW 4KM TROPICAL CYCLONE FORECAST SYSTEM

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Introduction

Dedicated tropical cyclone NWP assimilation and prediction systems have been run by the Bureau of Meteorology (BOM) since the debut of TCLAPS back in 1999 (Davidson and Weber 2000) and the current operational TC NWP system is the APS2 version ACCESS-TC which was operationally commissioned in Nov 2016 (BNOC, 2016). It runs on a 33°x33° grid centered on the cyclone of interest, relocatable anywhere within the nesting ACCESS-G Greater Asia tropical model domain over the western Pacific and eastern Indian Oceans. Up to 3 concurrent domains can be run at any time.

The current APS2 ACCESS-TC2 system uses a horizontal grid resolution of 0.11° (approximately 12km) which is simply too coarse to correctly simulate the depths and intensities typically found in real world tropical cyclones. A new higher resolution APS3 version of ACCESS-TC is now under development within BOM targeted to be ready for operational implementation before the 2018/19 cyclone season.

The new APS3 ACCESS-TC (a.k.a. "ACCESS-TC3") utilises a horizontal resolution of 0.036° (approximately 4km). At this resolution, the model can be run in convection permitting mode rather than using a parameterised convection scheme. The model physics configuration is expected to be based on the RA1-T tropical model settings under development by the UK Met Office as part of the Regional Model Evaluation and Development (RMED) process. RA1-T differs from the mid-latitude RA1-M settings primarily in the PC2 cloud scheme and revised unstable BL functions. RA1-M also uses stochastic BL perturbations and a revised free atmospheric mixing length.

APS3 ACCESS-TC will use tropical cyclone specific background error covariances which have been derived from a training set of paired forecasts for 409 tropical cyclone instances between July 2015 and February 2016 and utilise a new background error covariance formulation within the variational assimilation that allows more realistic, smaller scale increments

This talk will present initial results from this developmental ACCESS-TC3 system.

References

ADDING VALUE: THE ESA-MARINE - PHASE 1: THE FIRST STEP TOWARDS AN OPERATIONAL NOW-CAST/FORECAST OCEAN PREDICTION SYSTEM FOR SOUTHERN AUSTRALIA

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This talk will be given through the eSA-Marine website:


Background

The enhanced sustainability and profitability of fisheries and aquaculture depends the successful management of threats that arise from toxins, viruses and harmful algal blooms. Trajectory forecasts of such hazards are needed to provide time for adequate management response (e.g., shifting tuna pens). A forecast of ocean weather (currents, waves and sea level) will also assist in the scheduling of maintenance of marine infrastructure (e.g., finfish pens) and be of use to professional and recreational divers and fishers, and mariners more generally.

Reducing vessel time costs to fisheries and aquaculture is also of importance and examples include a better knowledge of target fish habitat and optimal routing of vessels to take advantage of ocean currents.

What the report is about: aims and objectives

In all cases above, there is a need for accurate now-casts and forecasts of ocean currents, temperature and sea level. To this end, and for the first time, a high-resolution, now-cast/forecast system for ocean currents, temperature and sea level has been built for Australia’s southern shelves and with a focus on the needs of fisheries and aquaculture. The system is meant as a “phase I” system that can be used in both real-world applications, and to provide a demonstration product to explore further developments needed to support southern Australia’s fisheries and aquaculture.

Methodology

The eSA-Marine system adopts data assimilation, where real time satellite sea surface temperature (SST) and sea surface height (SSH) are used to improve the predictions of the system. An additional feature is that the system is that three models are used to telescope information down from a 10 km grid global model, (OceanMAPS), to a 2.5 km grid shelf model [the Southern Australian Regional Ocean Model (SAROM)] and finally, to the 500 m scales of the Two Gulfs Model (TGM) needed to provide predictions at the scales of oyster leases and
finfish pens. A schematic of the eSA-Marine Systems modelling is shown in Figure 1 below. The system predictions are in good agreement with data from ocean moorings and field surveys.

![Schematic of eSA-Marine Systems modelling](image)

**Figure 5.** The above shows the flow of boundary information from the global (10 km grid) OceanMAPS to the SAROM regional model (2.5 km grid) and finally to the very high 500 m grid Two Gulfs Model (TGM).

**Results – adding value**

The eSA-Marine system now-casts and forecasts are easily and routinely available on the web at: [http://pir.sa.gov.au/research/esa_marine](http://pir.sa.gov.au/research/esa_marine). The web site contains several illustrations and scenario studies of how the results have and can be used to assist fisheries and aquaculture. It should be read in conjunction with this report. Several key results and implications are:

- **Pathogen trajectories:** these have been determined for three scenarios using the TGM and are presented in the web site. It is planned that these will progress to simulated POMs and Harmful Algal Blooms outbreaks in “trial” response exercises led by PIRSA Fisheries and Aquaculture (Shane Roberts): implication - allow for mitigation (e.g., move pens)

- **Pelagic fish habitats:** For SBT, the now-cast/forecasts of surface and bottom ocean temperature in the eastern Great Australian Bight have already provided information to the ASBTIA for likely habitats (18 - 20 °C) during the December-March period of 2015-2016. Temperature and salinity now-casts/forecasts have also been used by industry for this period to assist with the likely locations of sardines: implication - save fuel/time.
• origins of mass fish mortalities,
• lobster pot retrieval, ocean weather,
• optimal ship routing and
• fundamental fisheries and oceanographic research.

There are several other non-fisheries marine applications ranging from storm surge prediction, to sea level effects on marine harbor usage and search and rescue.

**Recommendations**

A more accurate and useful phase II eSA-Marine System will involve several improvements of that presented here; a) further tests of model accuracy; b) on-time now-casts; c) inclusion of the effects of wind and waves in the optimal ship routing; d) inclusion of Coffin Bay in eSA-Marine and ; e) graphical output.

Several other recommendations are detailed in Section 7
RAINFIELDS 3: REAL-TIME RADAR QUALITY CONTROL AND PRECIPITATION ESTIMATION

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The Australian radar network currently consists of 58 operational radars of varying technologies, frequencies, functionalities, and outputs. By number, this is the third largest network in the world behind China and the USA. In terms of radar infrastructure per capita, Australia leads the world with an approximate average of one radar per 400,000 people. The design of the network is focussed on covering coastal areas that are affected by tropical cyclones and areas of significant population.

The users of weather radar data are increasingly moving away from qualitative applications that are based on data visualisation towards quantitative rainfall estimations that are used in hydrological and other models. The Bureau completed the development of Rainfields2 in 2007 which delivered quantitative products for the four major urban areas of Australia. In 2012 work started on Rainfields3, which was designed to be able to generate products for all 58 radars in the network. Rainfields3 is close to being fully operational and the process of moving end users over to the new system has begun.

This talk will provide an outline of the algorithms in Rainfields3, details of the current products and verification capabilities, and a discussion of upcoming improvements to the system.
WHAT CAN OUR NEW OPERATIONAL DUAL-POLARIZATION RADARS DO FOR YOU?

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Abstract

The Bureau of Meteorology has embarked on a journey to upgrade the Australian operational radar network to benefit from dual-polarization technology. The first step of this project was to upgrade the existing S-band 1-degree beamwidth radars of four capital cities (Melbourne, Sydney, Brisbane and Adelaide) to dual-polarization. This first step has just been completed, with the four radars now back online. The second major step will be the progressive replacement of old radars with new dual-polarization radars as part of the planned roll-out of the network. A new tender procedure is currently being finalized to identify the partner radar manufacturer.

Extensive research has been conducted internationally and nationally to leverage from dual-polarization observations and deliver new and outstanding services to the community. In this presentation, I will describe what dual-polarization is, and what new opportunities dual-polarization offers to the public, from improved data quality control allowing for a better selection of radar data to be assimilated in our numerical weather prediction model, improved quantitative precipitation estimation when it matters (extremes), to hail detection, sizing, and nowcasting.
THE AUSTRALIAN WIND PROFILER NETWORK: OPERATION, ASSIMILATION AND RESEARCH

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Introduction

The Australian Government Bureau of Meteorology installed a network of 9 wind profiling radars (WPRs) across Australia, with the final profiler being installed in 2017. These radars provide vertical profiles of the horizontal winds for both forecasting and ingestion into Numerical Weather Prediction (NWP) models. There are two WPR classes, with Boundary Layer Profilers (BL/BLP), intended to provide winds from 300 m to 7 km, in Ceduna, Mildura, Cairns, Coffin Harbour and Mackay, and Stratospheric Tropospheric (ST) Profilers (ST/STP), intended to provide winds from 500 m to 20 km, in Halls Creek, Tennant Creek, Carnarvon and Longreach. These new systems complement an existing Bureau network of four BL profilers installed at Sydney, Launceston, Canberra, and East Sale, which underwent software and minor hardware upgrades as part of the project. Another system, intended for training and as a hot spare is located at Broadmeadows. In addition to the operational Bureau network, ATRAD Pty Ltd, the University of Adelaide, the Australian Antarctic Division and Mt Isa Mines also operate profilers in Adelaide, Davis Station in Antarctica and Mt Isa, respectively, which when combined, create a network of 18 instruments across Australia. While Australia has had multiple research and operational profilers in the past, we believe the profiler coverage is now sufficiently dense as to call it the Australian Wind Profiler Network, as shown in Figure 6.

The BL systems utilize the Spaced Antenna Full Correlation Analysis (FCA) technique to measure winds. The array consists of 27 Yagi antennas, arranged in 3 groups of 9 on a square grid, with the centroid of each square on the vertices of a triangle. The system uses the entire array to transmit, and receives separately on the 3 sub-groups, with a beamwidth of approximately 30° on receive, and 18° on transmit. BLPs typically operate with interleaved low and high modes, with a dwell time of approximately 1 minute, thus generating a low and high mode wind profile every 2 minutes.

Radars utilizing the spaced antenna FCA technique at VHF are known to measure excellent agreement in direction, but underestimate the wind magnitude by 5-10%, when compared to other measurement techniques. This underestimation is true in all regions of the atmosphere, and in comparison to different instruments such as radiosondes and Doppler radars (see e.g., Reid and Dolman, 2010). The exact cause of the magnitude underestimation is unknown, but it results from any effect that suppresses the correct value of the cross-correlation functions of the fading time series calculated between the antenna pairs. Following an extensive campaign comparing BL FCA data to radiosondes at multiple Australian sites, an empirical correction was
derived. Corrected magnitudes demonstrate excellent agreement in comparison to other wind measurement techniques, thus permitting the use of the spaced antenna FCA technique in an operational environment. Further details of the correction can be found in Dolman & Reid [2014]. This result is significant, as radars utilizing this technique, particularly when desired height coverage is limited to the troposphere, can be deployed on a much smaller footprint, and employing much lower powers than ST systems (see e.g., Vincent et al., 1998).

The ST radars utilize the Doppler Beam Swinging (DBS) technique, as commonly used by other weather agencies. The STPs are composed of 144 Yagi antennas, arranged on a 12 by 12 square grid. The entire array is used for both transmit and receive, with a beam width of approximately 7°. Electronic phase delays are used to steer the beam 15° from vertical in any of the cardinal directions. While any configuration is possible, the STP typically operates in a three-beam arrangement, consisting of beams directed to the vertical, north and east directions. As for the BLPs, the STPs typically operate in interleaved low and high modes, with a dwell time for each beam of approximately 1 minute, thus taking 6 minutes to generate a low and high mode wind profile.

Historically, VHF radars operating in DBS mode in the lower part of the frequency band were designed to measure winds to as high an altitude as possible, thus employing large transmitter powers and physically large antenna arrays. Problems with sampling the lowest altitudes arise from receiver ringing, poor transmit/receive switch recovery and ground clutter when large arrays and large transmitter powers are employed (see e.g., Vincent et al., 1987; Reid et al., 2005), and so earlier systems were typically limited by their first useable range gate, and were usually unable to sample the first kilometer of the atmosphere. To improve low level performance for the operational STPs, and begin sampling as close to the ground as possible, ground clutter, ringing, transmit/receive switches and general system noise were individually addressed and minimised. The BoM operational STPs are typically able to measure winds from 2x the transmitted pulse length.
In an operational forecasting environment, data must be quality controlled in an effective manner, such that wind profiles presented to forecasters are as clean as possible and free from outliers. The BoM operational profilers report WMO standard BUFR messages every 30 minutes, and thus represent the average of 15 individual low/high mode wind profiles for the BLPs, and 5 individual low/high mode wind profiles for the STPs. These averaged wind profiles are first subjected to a rigorous pattern recognition quality control procedure, based on Weber and Wuertz [1991]. For the BLPs, quality control is performed on the magnitude and direction, while for the STPs, the radial beams are used as the basic data block, with the wind magnitude and direction calculated from the averaged radial velocities. In both cases, each individual point within the data block to be averaged is compared to its neighbours in a series of tests, thereby attempting to remove outliers and average only the remaining ‘good’ points. The quality control process is described in detail in Dolman and Reid [2014]. Quality controlled winds are then output as both system standard and WMO standard BUFR messages every 30 minutes.

**Data Use**

**Desktop forecasting**

As stated above, the BoM operational profilers report horizontal and vertical winds every 30 minutes, which are available for desktop use by forecasters. These data are used in a variety of ways, depending on location, expertise and individual preference. Examples include:

- Verifying low level jet onset time and strength, particularly useful to aviation clients
- Gradient winds for seabreeze and fog forecasting
- Steering winds in thunderstorms
- Aviation forecasts, particularly for ground-truthing models when deciding whether to issue a SIGMET
- Fire weather
- Analyzing steering winds in mid-levels for the direction developing convection will take

The Australian Wind Profiler Network has also provided both greater information gains on previously known phenomena, such as the frequency of low level jets at Tennant Creek, and also previously unknown phenomena, such as a small temporal scale wave pattern at Ceduna, associated with the formation of the convective boundary layer. During the 2011/12 summer, the Ceduna profiler experienced more than 40 events of up to six hours of data dropout. These events were always accompanied by a characteristic high signal to noise ratio, implying data should be available. Investigations revealed an oscillatory trend/wave structure in both the horizontal and vertical wind components, which was subsequently rejected by the quality control measures across the averaging period. This means the profiler is measuring winds as it should, but the averaged wind value is not accepted because the associated variance is outside the limits intended to detect unreliable data. These data dropout events varied in both height coverage and time duration, but were predictable in other regards. The effect began near 0900 UTC, was generally associated with the formation and deepening of the convective boundary layer, and generally occurred when conditions were warm, dry and pre-frontal with a high to the
East of Australia. While the exact cause of the wave is yet to be determined, the effect is now known and noted, and quality control procedures have been modified to allow these wind data to pass.

Assimilation

In addition to desktop use by Australian forecasters, data from the Bureau profilers are available on the GTS (see e.g., http://www.eumetnet.eu/radar-wind-profilers), and are currently being ingested into both Australian and global NWP models. In addition to Australia, there are several cohesive profiler networks such as those in Japan, France and Germany, and many other profilers of various types and frequencies across the globe. The impact of these instruments, or in fact any instrument, on global NWP is the subject of ongoing research, and presents significant challenges. Data quality, timeliness of data delivery, frequency of observation and density of like measurements are among the variables contributing to the challenge. Criteria of data acceptance also vary across the major models, which leads to data acceptance in some models where it is rejected by others. The impact of the Australian network is typically equal to or better than other instruments, mostly due to the sparsity of other like measurements. Work on measuring the direct impact of the Australian network on the Australian Community Climate and Earth-System Simulator (ACCESS) has also begun, and preliminary results highlight some interesting features and future directions for the network.

Research

In addition to operational use, VHF wind profilers can be used for additional data or research purposes, the most notable examples being the retrieval of precipitation information, radar tropopause detection (e.g., Alexander et al., 2013), and turbulence monitoring (e.g., Holdsworth et al., 2001).

Conclusion

The Australian Wind Profiler network has proved valuable both operationally, and for research purposes. Data is currently being ingested into global NWP models, and generally making positive impacts. The network has also been used for greater information gains on weather phenomena, and is a useful research tool.

References


UTILITY OF CONVECTION-ALLOWING MODELS AND ENSEMBLES FOR HIGH-ImpACT WEATHER ForesTATING

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Introduction

The NOAA/Storm Prediction Center (SPC) is an operational unit in the National Weather Service (NWS) responsible for issuing forecast products for general thunderstorms, severe thunderstorms (i.e., those producing tornadoes, large hail, and damaging wind), and hazardous winter weather and fire weather events over the contiguous United States (CONUS). These high-impact weather events occur at fine spatiotemporal scales, so numerical forecast models run at high resolution can provide useful guidance in forecasting these events. Specifically, models run with a horizontal grid spacing of less than ~4 km begin to explicitly represent deep convective processes without a convective parameterization scheme. Models run at this resolution are commonly referred to as convection-allowing models (CAMs). Some aspects of CAMs and CAM ensemble systems are discussed in this abstract along with their utility in forecasting high-impact weather events.

Convection-Allowing Models

Real-time CAM guidance has been utilized in operational severe weather forecasting for more than a decade at SPC. Testing and evaluation during field programs, such as the Bow Echo and MCV Experiment (BAMEX) in 2003, and annual Hazardous Weather Testbed (HWT) Spring Forecasting Experiments (SFE) since 2004 have played key roles in this transformative process. CAM output complements traditional larger-scale, environment-based forecast approaches by providing unique information on convective initiation, mode, intensity, and evolution that can relate more directly to severe weather potential and hazard type (e.g., Done et al. 2004; Weisman et al. 2008). For example, through explicit thunderstorm prediction, CAMs provide information on the potential for discrete supercells, which typically pose a greater tornado threat than storms that develop in a more linear fashion.

Continued development efforts over the past decade have led to improvements in deterministic CAMs over a CONUS domain, including the generation of specialized output fields for explicit simulated storm attributes and hourly maximum fields (HMFs; Kain et al. 2010). HMFs track specific variables at every time step during model integration and output the maximum value during the previous hour, providing a computationally efficient way of identifying peak intensities of simulated storm attributes. Some of the storm-attribute HMFs include 1-km AGL simulated reflectivity for diagnosing convective mode and intensity, 2-5 km AGL updraft helicity (UH; Kain et al. 2008) for representing a rotating updraft in a simulated storm (i.e., supercell), updraft speed for providing a measure of convective overturning and hail potential, and 10-m AGL wind speed for identifying convective wind gusts. Forecasts of UH, in
particular, can provide useful information to forecasters regarding organized severe weather potential (e.g., Sobash et al. 2011).

**CAM Ensembles**

Deterministic CAM forecasts often differ, especially in weakly forced situations, even though each of the forecasts may appear as plausible solutions within the specific mesoscale environment. These varying solutions reflect limits to predictability on the convective scale, which prompted efforts to develop CAM ensemble systems to quantify uncertainty and provide a range of possible convective storm solutions. The first real-time CAM ensemble system was developed by the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma for the 2007 HWT SFE. In subsequent years, exploration of experimental CAM ensembles also expanded across the community with CAPS, SPC, NSSL, NCAR, GSD, and the USAF developing systems with varying configurations and levels of complexity. In early 2011, the SPC Storm Scale Ensemble of Opportunity (SSEO; Jirak et al. 2012) became the first real-time experimental CAM ensemble produced year-round, providing operational forecasters with guidance for severe storms, heavy precipitation, fire weather, and winter weather.

**CAM Ensemble Design**

One primary goal of annual HWT SFEs is documenting performance characteristics of experimental CAM ensembles. The number of CAM ensembles examined in the SFE has increased over the years, including six independent CAM ensembles in 2015. While major advances have been made in processing, visualizing, and verifying these large and complex datasets, progress toward identifying optimal CAM ensemble configurations has been inhibited because the different systems have been independently designed by the diverse collaborators. As a result, it is difficult to attribute and understand differences in performance characteristics among the different CAM ensembles.

Given this background and recent recommendations to NOAA by the international UCAR Model Advisory Committee to unify model development through a collaborative, evidence-driven approach, a much more coordinated effort was established for the SFE in 2016 with regard to CAM ensemble design. This was achieved by working with collaborators on a common set of model specifications (e.g., model version, grid-spacing, domain size, physics, etc.) so that the simulations contributed by each collaborator could be combined to form one large, carefully designed ensemble known as the Community Leveraged Unified Ensemble (CLUE). The 2016 CLUE was comprised of 65 members contributed by five research institutions, and represents an unprecedented effort to help guide NOAA’s operational modelling efforts at the convection-allowing scale. Eight unique controlled sensitivity experiments were designed within the CLUE framework to examine issues directly relevant to the design of NOAA’s future operational CAM-based ensembles.

Some of the general findings from the 2016 CLUE are summarized below:

- The multi-core ensemble strategy provided better probabilistic forecasts for severe weather and 24-hour probabilistic QPF than single-core ensemble forecasts (Clark et al. 2017).
For reflectivity, precipitation, and updraft helicity forecasts, the statistical improvement in forecast skill by increasing the size of the CAM ensemble was relatively small.

The ensemble comprised of members with radar data assimilation verified better than the ensemble without radar data assimilation through ~15 hours into the forecast cycle.

The SSEO verified objectively as well as or better than any CLUE subset for probabilistic reflectivity forecasts.

The findings from the 2016 CLUE support a few recurring themes regarding CAM ensemble design that have been observed over the past several years in the HWT SFE. First, a multi-core ensemble seems to provide improved probabilistic forecasts for severe weather through increased diversity. Second, a CAM ensemble on the order of ten (10) members appears sufficient to capture the majority of forecast skill for the Day 1 time period (i.e. forecast hours 12-36) given the current initialization/perturbation strategies. Third, CAM ensembles generally provide similar, useful guidance for next-day severe weather forecasting regardless of design and complexity. In fact, the SSEO, which began as an experimental poor-man’s ensemble at SPC to summarize information from multiple deterministic CAMs, has compared favorably to other formally designed CAM ensembles over the last several years in the HWT SFEs. Based on these results, the SSEO became operational at NCEP on 1 November 2017 in the form of the High Resolution Ensemble Forecast (HREF) system.

**CAM Ensemble Post-Processing**

Some post-processing techniques are utilized to help extract and summarize useful information from CAM ensembles. These techniques are primarily applied to the storm-attribute HMFs. One technique involves taking the temporal maximum of an HMF over some specified time period. Given the unique aspect of the storm-attribute HMFs, the maximum value each hour over the lifetime of a storm provides a simulated “storm track” and corresponding “swaths” of severe weather potential. Furthermore, extracting the temporal maxima over the period during which a SPC Convective Outlook is valid (e.g., 1200-1200 UTC) summarizes expected storm activity and severity over that time period in a single plot.

Another processing technique is used to account for spatial uncertainty and the lack of grid point agreement in the placement of storms among the CAM ensemble members. This technique involves taking the maximum value within a specified horizontal radius (i.e. neighborhood). Following the results of Harless et al. (2010) and the SPC probabilistic definition utilized in convective outlooks (i.e., within 25 miles of a point), the maximum value of storm-attribute HMFs is found within a 40-km radius. Probabilities are then calculated for a 40-km neighborhood and smoothed using 2-D Gaussian kernel density estimation (Hitchens et al. 2013) with a smoothing parameter of 40 km. This neighborhood approach provides meaningful probabilistic information when ensemble members have similar, but not identical, placement of storms.

Many of the typical ensemble display techniques (e.g., mean, maximum, exceedance probabilities) are utilized with CAM ensembles. Some of the most useful ensemble displays of the storm-attribute HMFs include spaghetti (paintball) plots, ensemble maximum displays, and
smoothed neighborhood probability plots. Spaghetti plots simply display each member in a different color for a given field and threshold (e.g., Fig. 1a). The ensemble maximum (e.g., Fig. 1b) provides an estimate of the upper-end of storm intensity for a particular forecast. Smoothed neighborhood probabilities (e.g., Fig. 1c) show the degree to which the models are in agreement with one another in the placement of storms and storm attributes. All three types of ensemble displays should be used in a complementary manner to better understand the distribution and characteristics of an ensemble HMF.

Figure 7. SSEO forecasts valid for the 6-h period ending at 00 UTC on 28 April 2011: a) 6-h spaghetti plot of $UH \geq 25 \text{ m}^2\text{s}^{-2}$, b) 6-h ensemble maximum of $UH \text{ (m}^2\text{s}^{-2})$, and c) 6-h smoothed neighborhood probability of $UH \geq 25 \text{ m}^2\text{s}^{-2}$ (%). In b) and c), the preliminary storm reports from this 6-h period are shown (tornado – red, hail – green, and wind – blue).

Summary

CAMs and CAM ensembles provide unique information regarding explicit storm-attribute information on convective initiation, timing, intensity, mode, and evolution. Through community collaboration, development, and testing within the HWT SFEs, forecasts from CAMs and CAM ensembles continue to improve, benefitting the SPC in its mission to provide accurate hazardous weather forecasts for the CONUS.

References


ACCESS CITY ENSEMBLE (CE3): TOWARDS CONVECTIVE SCALE ENSEMBLE NWP AT THE BUREAU

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Introduction

Many meteorological agencies run their own Numerical Weather Prediction (NWP) ensembles. NWP ensembles are designed to sample the possible future state of the atmosphere by acknowledging and attempting to account for sources of uncertainty in weather forecasting. High-resolution NWP ensembles are able to provide information on high impact weather events, and their uncertainties, on the time-scales of a few days.

The Australian Community Climate and Earth-System Simulator (ACCESS) City Ensemble (ACCESS-CE3 or CE3) is currently under active development and substantial progress has been made. This system leverages information from the third generation Australian Parallel Suite (APS3) Global Ensemble (ACCESS-GE3 or GE3) and the City deterministic system (ACCESS-C3 or C3) to generate a 0.0198° (~ 2.2 km), 12 member ensemble over six city domains shown in Figure 1. Early results from initial runs of CE3 are promising and are discussed below.

ACCESS CE3 System

ACCESS-CE3 is a convection permitting model (Clarke et al., 2016) based on the Parallel Suite 38 (PS38) Met Office Global and Regional Ensemble Prediction System (MOGREPS) high-resolution ensemble system, MOGREPS-UK (Tennant and Beare, 2014; Tennant 2015; Hagelin et al., 2017). CE3 is a 2.2 km grid-spaced system with 12 members, cycling four times a day over the six city domains, Figure 1. The blue dashed lines represent the location of the (second generation) APS2 city domains while the black lines represent the uniform core of the APS3 city domains (a slight offset has been applied to the APS2 Perth and VicTas domains for visualisation purposes. In fact, the APS2 and APS3 domains are exactly the same). All APS2 domains are fully encapsulated by the APS3 domains except the Darwin domain. This is due to the variable grid system (discussed below) that is used in the APS3 systems, which would extend the full APS3 Darwin domain (green lines in Figure 1) into the high elevation areas of Papua New Guinea, forcing a slight change in the location of the Darwin domain.

The variable resolution grid spacing is 0.036° (~ 4 km) from the boundaries (green lines in Figure 1) to the transition zone (red lines in Figure 1), approximately 40 grid cells into the domain. Grid spacing is reduced in the transition zone from 4 km to 2.2 km over approximately 22 grid cells, forming the inner uniform core of the domain (black lines). The variable resolution grid allows direct nesting of the Local Area Model (LAM) within a coarse grid
driving model by reducing the resolution mismatches at the boundaries, eliminating the requirement of intermediate grid length model runs (Tang et al., 2013).

The base initial conditions for CE3 are provided by C3, a 1.5 km resolution system with a 3D-Var Data Assimilation (DA) cycle which updates the first guess field with observational data. Initial condition perturbations and lateral boundary conditions are provided by GE3. The initial condition perturbations, the difference between the ensemble members and control member, are integrated with the base initial conditions to create unique initial conditions for each 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.

Figure 8: The location of the city domains. The dashed blue lines represent the APS2 domains. The green lines represent the outer boundary, the red lines represent the beginning of the transition zone and the solid black lines represent the uniform section of the APS3 domains.
Early Results: Visual Validation

Initial test runs of CE3 provide an insight into the value of the system as development continues. CE3 was run for May 18-20, 2016, to assess the functionality of the suite. An East Coast Low system impacted NSW during this time, providing the system with a strongly forced and wet case to work with. Though predominately a technical trial, the resultant forecasts show that the system produces realistic forecasts.

Figure 2 presents postage stamp CE3 forecasts over the ACCESS-SY domain. The red rectangle indicates the location of the Sydney Radar Mosaic, a mosaic of six radars covering the Sydney region. As expected for systems with large scale meteorological forcing, forecasts from each member are broadly similar. However, there are still noticeable differences within the ensemble. As an example, forecasts for the rainfall feature to the east of the radar domain range from a single organised band to multiple groupings of showers. The rainfall position also varies between members.

Figure 3 presents the 12 hour CE3 forecasts from the red rectangles in Figure 2, alongside the Rainfields3 gauge blended 30 minute accumulation observations. Rainfields3 observed a band of rainfall from the northwest corner to the centre of the domain. Each of the ensemble forecasts predicted a band of precipitation across the domain at this valid time. There are variations in the location and organisation of this feature within the ensemble. Another feature of these forecasts is the presence of showers just off the coast to the south of the domain which are also present in the observations. The ensemble forecasts rainfall features which appear to be visually similar to
the radar observations for the case study presented. Scientific trials and associated formal verification of the system are set to be undertaken in early 2018.

**Summary and Future Plans**

The Bureau’s first convective permitting, 2.2 km grid-spacing NWP ensemble, ACCESS-CE3, is under active development. Initial trials of a 12 member ensemble system capable of ingesting 3D-Var initial conditions from C3 have been successfully run. Visual inspection of the rainfall forecasts from this system indicate the ensemble produces rainfall features similar to those observed by the radar, for the strongly forced case presented here.

Currently, C3 is being upgraded from a 3D-Var system to a 4D-Var system, based on PS39. This necessitates upgrading the CE3 system, also based on PS39, to allow ingestion of 4D-Var initial condition data. Furthermore, an increase in the number of GE3 ensemble members will allow CE3 to also run 18 members. Scientific trials of this ensemble are set to be run in early 2018 with associated formal verification.

**References**


NEW DEVELOPMENTS IN THE BUREAU’S THUNDERSTORM PREDICTION SYSTEM – CALIBRATED THUNDER

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There is clearly an increasing need by many users of weather information to extract thunderstorm information from the output of numerical weather prediction models (NWP), but ‘raw’ NWP output fields are difficult to interpret in view of estimating the likelihood of thunderstorms. Late in 2016 a post-processing package, Calibrated Thunder (CT), went operational at the Australian Bureau of Meteorology. It produces uncalibrated and calibrated probabilities of cloud-to-ground lightning strikes in 3-hourly intervals on a 40 km x 40 km grid over Australia out to 2 days. NWP inputs are sourced from a 5-member lag ensemble of the ACCESS-R model which produces output on a ~12.5 km grid over Australia.

Operational demands have led to the development of two significant extensions to the original CT system. First, the Graphical Forecast Editor, the Bureau’s primary forecast production system, requires thunder probabilities up to eight days in advance. To achieve such a lead time, CT has been duplicated to run off input from the second release of the global ACCESS model (ACCESS-G2) with model fields written to a grid with ~24 km spacing. We will describe the adapted CT system setup and show how the CT reliability, accuracy and ability to distinguish between thunder events and non-events evolves with increasing lead time. Early validation over the 5-month 2016/2017 summer period indicate that CT remains sufficiently skillful for useful operational use out to 8 days, but only for afternoon and evening convection. Nocturnal convection is handled less skillfully by the system, and the system loses significant skill by day 4.

Second, the Bureau’s Extreme Weather Desk drafts daily national convective outlooks on a 20 km x 20 km grid. The CT system has also been adapted to produce 24-hour thunder probabilities on this finer grid. The novel derivation of the 24-hour calibrated probabilities and other new system features will be outlined, and verification results presented.
IMPROVED EXTREME WEATHER HAZARD PREDICTION AND COMMUNICATION THROUGH SCIENCE TO OPERATIONS

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The Extreme Weather Desk, embedded within the Bureau of Meteorology’s National Operations Centre, provides a national focus for extreme weather intelligence, and an additional layer of capability to respond to the increasing frequency of high-impact weather across Australia. The provision of extreme weather intelligence to the Bureau’s Regional Forecast Centres, the media, and high-level internal and external stakeholders and decision makers stems from a strong Science to Operations role in evaluating and implementing new science, techniques and guidance to improve processes, products and services.

An end-to-end forecast process for thunderstorm forecasting was trialled by the EWD during the 2016-2017 Australian Severe Weather Season. Probabilistic forecasts of thunder, large hail, damaging winds, heavy rainfall, tornado and combined severity were provided nationally on a routine basis to demonstrate the process and products of a potential future thunderstorm service. A daily verification product was produced that collated severe thunderstorm reports and observations, and provided an assessment of the convective environment and performance of automated guidance and new diagnostic parameters. Post-season objective verification completed the end-to-end forecast process and identified skill, systematic and individual biases that further refined the forecast process and strategies.

The EWD is also embarking on further work to demonstrate a potential future service that links the daily thunderstorm forecasts and warnings via rapid update short-term forecasts.

Over the past decade, targeted research has advanced the understanding of fire and meteorological processes; but embedding new knowledge and predictive techniques into fire weather forecasts have been slow. The EWD is currently conducting a national trial of advanced fire weather forecast products; the National Fire Outlook, that focusses on processes other than those captured in the standard fire weather service: the potential for dry lightning, significant wind changes, enhanced fire behaviour and deep plume development leading to pyro-convection.
IMPROVER - A NEW STRATEGY FOR INTEGRATED POST-PROCESSING AND VERIFICATION FOR THE CONVECTIVE SCALE AGE

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Introduction

The advent of convective scale NWP models with horizontal grid-lengths of order 1-4km has introduced huge potential for detailed local forecasting not previously possible, in particular much better representation of convective precipitation and of local orographically forced detail such as valley fog. However much of this detail is not deterministically predictable, for example the timing and location of convection or patchy low visibility, so that these models are best run in ensembles and require a probabilistic approach to post-processing systems to aid in their interpretation and generate automated forecast outputs. Met Office post-processing systems have evolved over many generations of lower resolution models, with separate systems for ensembles and deterministic models. While there has been some integration for the convective scale 1.5km UKV model and 2.2km MOGREPS-UK ensemble including use of neighbourhood processing to address spatial uncertainty, a recent review of post-processing science recommended a new approach to provide a fully integrated probabilistic system for the convective-scale age. A major project has been launched this year as part of the Met Office’s Transformation and efficiency programme to develop and implement a new post-processing system, IMPROVER, with the aim of replacing all the existing systems by March 2020. IMPROVER dataflow is illustrated in fig. 1 which defines four levels of processing:

- **Level 0**: raw model output on model-specific grids and data formats;
- **Level 1**: model output fields in standard gridded formats and vertical levels in NetCDF format, also used for sharing of model data inside and outside the Met Office;
- **Level 2**: internal-only stage of processing on individual model fields;
- **Level 3**: probabilistic forecast fields from a blended combination of models and ensembles.

Key features of this system will include:

- All processing conducted on standard grids (Level 1);
- A probabilistic approach including neighbourhood processing to consistently compare and combine ensemble and deterministic model outputs;
- A blending approach to provide optimal forecasts combining data from multiple models and ensembles;
- Extraction of site forecasts and any optimisation using site observations occurring at the end of the chain (level 3), to improve consistency between site and gridded forecasts;
- Verification at every stage so that the benefit of each component can be better understood;
- A modular software architecture allowing plug-in components to be included as required.
Implementation Progress

Implementation of the new strategy started in 2016 with the StaGE “decoupler” (Standard Gridding Engine) which presents all model outputs on standard grids in CF-compliant netCDF format. As well as aiding the blending of different models in the post-processing system, these formats are also used for all model output distribution through the Met Office’s new “Service Hub” which will allow downstream applications such as forecast product generation to be decoupled from changes to individual NWP models. All four of the Met Office’s core NWP systems, Global model and global ensemble MOGREPS-G and the convection-permitting UK model and UK ensemble MOGREPS-UK, were delivered to the Service Hub through StaGE in Oct 2017.
IMPROVER development started in 2016-17 with the development of two proof-of-concept demonstrations showing the ability to build a dataflow with modular plug-ins combining multiple models and to verify the stages. In September 2017 we delivered the first prototype IMPROVER system with a full end-to-end capability including:

- Wind downscaling
- Neighbourhood processing
- Convection diagnosis (to enable future post-processing specifically for convection such as convective gust diagnosis)
- Probabilistic time-lagging and blending of hourly-cycling UK model with 6-hourly cycling MOGREPS-UK
- Generation of probabilities & percentiles
- Spot forecast generation at Level 3
- Verification

Fig. 2 illustrates a simple schematic of the blending of MOGREPS-UK and hourly-cycling UK model (UKVx) together with a plot of grided probability of windspeed exceeding 10ms\(^{-1}\) which includes orographic downscaling of windspeed.

**IMPROVER Technology and Collaboration**

IMPROVER is being built using Python following existing standards to ease sharing of data and code development and encourage collaboration. Data are stored and output in CF-compliant netCDF format. Software is developed as modular, unit-tested code, making extensive use of NumPy and the open-source Iris libraries. IMPROVER code is itself mostly open-source on GitHub to facilitate collaborative development. Verification capabilities are based on the Met Office’s VER and VerPy systems and will allow verification of each step of the processing.
chain individually so that each module can be assessed for its contribution to the overall forecast improvement and included or not as appropriate.

**Visualization and Meteorologists’ Dashboard**

One of the key challenges for a post-processing system today is condensing and summarising the key messages from the vast quantities of data available from ensembles and rapid update cycles such as the Met Office’s hourly-cycling UK model runs and planned hourly-cycling MOGREPS-UK. The IMPROVER project itself provides minimal visualization, mainly for the benefit of developers (fig 2) but is working in close collaboration with another project under the Transformation and Efficiency programme to deliver data to meteorologists from the Service Hub. As Level 1 StaGE data and Level 3 IMPROVER data will be presented in very similar formats on identical standard grids meteorologists will be able to ingest both model data and post-processed fields and compare them directly for analysis and guidance development. Blending NWP outputs is usually an effective way to provide the best quality probabilistic forecast, but meteorologists will always want to compare this with the individual models and ensembles.

Another output of the new system will be a set of forecaster “dashboard” products on the forecaster workstations to provide headline alerts and messages to operational meteorologists on high-impact weather risks highlighted in the post-processed probabilities. Some of these will incorporate existing high-impact weather tools (Mylne et al, 2017), which will be migrated to run from IMPROVER blended probabilistic forecasts, but the dashboard will also develop new quick-look and attention-getting facilities based on IMPROVER outputs to help draw meteorologists’ attention to key weather hazards and risks. Some examples of what these might look like are illustrated in fig. 3.

![Fig 3: Examples of forecaster dashboard type products to highlight extreme or high-impact weather risks from the IMPROVER probabilistic fields.](image)

**References**

MACHINE LEARNING INTEGRATION INTO HIGH IMPACT WEATHER FORECASTING SYSTEMS

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The amount of available weather data continues to increase rapidly with the advent of finer spatio-temporal resolution numerical weather prediction (NWP) models, satellites, and radar data. Human weather forecasters currently cannot interpret and synthesize all of the available weather data in the time required to issue a forecast. As a result, they may miss crucial pieces of information that could have improved their forecasts. Machine learning is a powerful set of tools for discovering patterns in large datasets and utilizing those patterns to make optimized predictions. Naïve application of machine learning models, however, can result in models that generalize poorly, produce non-physical predictions, or lack coherence across space, time and correlated variables. The purpose of this presentation is to demonstrate how machine learning can be properly integrated into high impact weather forecasting systems to produce robust predictions that are trusted by weather forecasters.

This presentation examines how machine learning is integrated into the high impact weather forecast process through the context of forecasting severe hail. Potential hail storms are identified in convection-allowing model output and are matched with radar-estimated hail swaths. Information about storm structure and environment are extracted from each potential hailstorm. Random forest machine learning models estimate the probability of hail and the spatial hail size distribution. Methods for constraining and evaluating machine learning models, such as multi-task learning, grid search, and cross-validation, are discussed. Machine learning hail forecasts are evaluated against other physic-based hail forecasting approaches, including WRF-HAILCAST and microphysics-estimated maximum hail size. Comparisons across different regions, time periods, and environmental conditions are performed. Variables critical for hail forecasting are identified through a permutation variable importance approach. Deep learning models for encoding spatial storm information are also introduced and compared against more traditional machine learning encoding methods. Finally, challenges in transitioning machine learning models to operations, ways to increase trust in automated guidance, and the benefits and drawbacks of different levels of forecast automation are discussed.
DISENTANGLING THE WEATHER MANIFOLD

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Introduction

The quality and volume of data generated by Numerical Weather Prediction (NWP) has steadily increased for the last 5 decades. On the other hand, the methods and tools used for its interpretation have not developed at the same pace. Weather forecasting is still an activity in which humans have to interpret NWP to generate different products. Forecasters are often overwhelmed by the volume and number of physical parameters produced by current NWP, and interpretation is usually based on a small fraction of the available data.

Machine learning is currently an active field of research which studies the underlying patterns on data. Neural networks and Deep learning techniques in particular, have recently proven an enormous success by achieving unprecedented results on different domains. In this work, we study the use of deep learning techniques to interpret NWP data. We offer a comparison on how these techniques compare to more traditional methodologies and we also provide some insight into the techniques used to extract the spatial and temporal information contained in the data.

Methodology

Data preparation

For this work we used the publicly available ERA-Interim (Dee et al. 2011) climate reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The data assimilation system used to produce ERA-Interim is based on a 2006 release of the IFS (Cy31r2). The system includes a 4-dimensional variational analysis (4D-Var) with a 12-hour analysis window. The spatial resolution of the data set is approximately 80 km (T255 spectral) on 60 vertical levels from the surface up to 0.1 hPa.

We extracted an extended area over Europe, creating a 6-hourly temporal series for geopotential height at the 1000, 700 and 500 pressure levels of the atmosphere. 6-hour accumulated precipitation data was extracted for the closest grid points to 5 main cities in Europe (Dublin, London, Amsterdam, Paris and Berlin). These data were transformed into a labelled [dry, rain] using 1 litre as the threshold. Figure 1 represents the resulting dataset.
The geopotential heights data are used as the input to train different machine learning methodologies using the precipitation values for the different cities as labels.

**Evaluation of machine learning methodologies**

NWP is an example of a structured dataset that encode both spatial and temporal information. Deep neural networks have proven to be especially effective in extracting spatial and temporal patterns from data. More specifically, research around Convolutional Neural Networks (CNN) (Krizhevsky et al. 2012) has proven to be very effective in solving image classification and segmentation problems. Similarly, Recurrent Neural Network (RNN) (Graves et al. 2013) have demonstrated state-of-the-art results in tasks involving the temporal dimension, such as speech recognition or the interpretation of video sequences.

Using traditional methods, such as logistic regression or Random Forest (Breiman 2001) as the baseline, these methodologies are used to interpret geopotential height fields and associate them with rain events at different locations. An overview of the differences in accuracy and computational cost between the different techniques will be provided.

**Acknowledgements**

The authors wish to acknowledge funding from the Australian Government Department of Education, through the National Collaboration Research Infrastructure Strategy (NCRIS) and the Education Investment Fund (EIF) Super Science Initiatives through the National Computational Infrastructure (NCI), Research Data Storage Infrastructure (RDSI) and Research Data Services (RDS) Projects.

**References**


WATCHING CLOUDS IN THE CLOUD: FORECASTING THE EVOLUTION OF CLOUD OBJECT ENSEMBLES WITH COMPUTER VISION AND DEEP LEARNING

Emile Jansons

Bureau of Meteorology

This presentation describes the development and performance of a real-time cloud analysis, classification and prediction system. Cloud object features are extracted from multi-spectral geostationary satellite imagery and clusters evolve through the splitting and merging of objects identified in successive images. A recurrent neural network is used to classify objects into developmental classes based on properties such as growth rate, velocity, texture and shape.

The observed motion of each object cluster is combined with the assigned development class to predict the evolution of the cluster. The lagged ensemble of forecasts for each cluster is verified against incoming observations to provide feedback to the object tracking and developmental model classification systems. Real time forecast skill as a function of lead time is calculated for each cloud cluster and a performance weighted ensemble of forecasts is used to generate a probability density map for the future distribution of the cluster. Cloud object forecasts typically demonstrate significant skill at 60-90 minutes lead time.

Based on user defined spatial, temporal and probability thresholds the system is able to generate proximity alerts and when combined with lightning data, probabilistic thunderstorm threat maps.
SUPPORTING LARGE SCALE EXPERIMENTAL WORKFLOWS
ON THE NERSC HPC

Katie Antypas

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The National Energy Research Scientific Computing (NERSC) Center is the mission HPC computing facility for the US Department of Energy, Office of Science. As the NERSC workload grows to include more data analysis from experimental and observational facilities such as light sources, telescopes, satellites, genomic sequencers and particle colliders, scientists require new capabilities to efficiently process their workflows that have not been traditionally supported on HPC systems. Users’ workloads now require containers, real-time computing, machine learning tools and streaming analysis. This talk will describe NERSC’s efforts to partner with experimental facilities to support these new workflow paradigms.
TRENDS IN COMPUTATIONAL ARCHITECTURES AND APPLICATIONS OVER THE COMING 5 YEARS

Phil Brown

CRAY

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This talk will review the computational architectures utilized for Earth Sciences applications, general scientific computing and emerging data analysis applications today and discuss some of the expected trends over the coming years.

The talk will look at both the hardware, software and IO platforms required by these different application types, and their implications for system design.
OPTIMISING STORAGE FOR SCIENCE AND ANALYTICS

Justin Glen

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As general purpose storage drifts to the cloud, storage suppliers are designing increasingly specialised and high performance systems for specific workflows. DDN will describe some of the characteristics of storage systems optimised for scientific research.
TOOLS AND PLATFORMS FOR DATA ANALYTICS, DEEP LEARNING, AND VISUALISATION

Werner Scholz

XENON Systems

The recent popularity and success of Deep Learning methods can be attributed to 1) new approaches to the design and optimisation of neural networks, 2) the development and publication of a variety of open source Deep Learning frameworks, and 3) the capabilities of modern accelerator designs.

In this presentation, we will review the basic concepts behind Machine Learning and Deep Learning, their application in weather modelling, and new systems, platforms, and technologies optimised for Analytics, Deep Learning, and Visualisation.

[Werner has more than 15 years’ experience with high performance computing systems – from individual workstations to massively parallel HPC clusters and large storage systems. He is also the developer of an open source finite element simulation package, which uses MPI, OpenMP, and GPU parallelization techniques. It is in used by academic and industrial research organizations around the world.

Werner has a PhD in physics from the Vienna University of Technology in Austria, where he specialized in computational physics and magnetic materials. He is the author of more than 80 journal articles in the area of computational physics and magnetic nanostructures and co-inventor of 15 patents related to magnetic storage technologies.]
DECIDING TO ACT: FACTORS INFLUENCING DECISION MAKING IN THE BRISBANE FLOODS AND TC DEBBIE

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For most of us, hazard preparation is not something that happens as part of our everyday lives, it is something that requires a conscious decision to act. There is a perspective common among decision makers and emergency managers that decisions on disaster preparedness and evacuation are made rationally, based on expert information that is available both in the months in advance of a potential hazard and at the onset of an event. However, the reality is that some household residents do not realise that preparedness messages are relevant to them while others adopt a “wait and see” approach before acting at the last minute. Further, decisions about actions such as evacuating usually include considerations that are emotionally based and often without understanding of the potential consequences.

This presentation highlights some of the factors found to influence decision making in a series of studies focused on two events: flooding in Brisbane and Ipswich in South-East Queensland (SEQ); and, the impact of Severe Tropical Cyclone Debbie on North Queensland (NQ) communities in 2017. The SEQ research was conducted through a series of largely quantitative postal surveys following the 2011 and 2013 floods that collected a range of information considering community reactions to warnings and the range of preparation actions. Based on those findings, the NQ research used interviews to focus on the information used in support of decision making in the days before and during the arrival of TC Debbie.

The studies found that a range of factors are considered in household decision making, including: the need for appropriate risk perception for warnings to be heard let alone acted upon; a lack of personalisation of warnings; the emotional attachments to pets and the anxiety that is produced by interacting with strangers at evacuation centres; and the key role of social networks in all aspects of decision making.

The presentation will provide a discussion of the ‘take-home’ messages arising from the research outcomes, in the context of effective risk communication.
ON THE NEXUS BETWEEN FORECAST UTILITY AND SYSTEM DYNAMICS: A WATER RESOURCE PERSPECTIVE

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The key attributes of a forecasting scheme are skill, reliability and lead time relevance. Accepting that perfect streamflow forecast schemes are beyond our grasp and that each new quantum of research is likely to see diminishing returns, the question arises, what are the requisite levels of skill, reliability and lead time for the forecast scheme to be practically useful? Answering such a question requires an explicit evaluation of the forecasting scheme in the context of its application. Two key considerations are the manner in which decisions, that control system performance, use forecast information and the impact time, which is the time taken for the consequences of those decisions to be felt by system users. Fundamentally the utility of the forecast system depends not only on its inherent skill and reliability over relevant lead times but also on how the decision making system uses the forecast information. These issues will be explored in the context of water resource systems whose impact times range from short times typical of regulated river basins, which have to meet downstream irrigation needs at daily time scales, to long times typical of urban systems, which have to be secure against extreme drought. It will be argued that the utility of a particular forecast system can only be meaningfully evaluated if system decision making is optimized to make best use of the information provided by the forecasting system and that high skill is not always necessary.
FORECASTING REQUIREMENTS FOR CONTEMPORARY AND FUTURE RIVER SYSTEM MANAGEMENT

Neville Garland

(MDBA)

The presentation aims to provide an insight into current and future water delivery and management challenges with specific reference to the River Murray System, and more broadly the Murray-Darling Basin.

Profound changes are taking place as water is recovered from previous consumptive uses for delivery to the environment. Demand patterns and ways of operating are changing considerably and, along with changing climate, new water policy initiatives and increasing volumes of water trade, the challenges and uncertainty around system management are increasing. In this rapidly changing environment, the traditional approaches of managing river systems using historical data and previous experience, are becoming less effective. To meet the new challenges, river managers are investing in improved tools and approaches increasingly reliant on forecasts of weather and streamflows. Shorter term forecasting has always been important but in delivering the higher flows needed for environmental benefit the stakes are higher and improved forecasting is imperative. Probabilistic forecasts out a month will become an important tool in managing environmental water portfolios and system risks. And seasonal streamflow forecasts based on dynamic modelling approaches will provide river managers and water users alike with the best available outlooks as climate continues to change. Australia is widely regarded as being on the forefront of water policy reform safeguarding environmental, social and economic needs. Investment in forecasting capability is essential to effectively deliver upon these reforms.
Understanding and Quantifying Uncertainties in Ensemble Short-term Streamflow Forecasts

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Ensemble streamflow forecasts for lead times of up to 10 days can support risk-based real-time management of water resources and emergency responses to flooding. Ensemble streamflow predictions have been shown to be more accurate than deterministic predictions (e.g. Bennett et al. 2014), and international experience suggests that providing formal estimates of forecast uncertainty to users can lead to better and more robust decision making under certain conditions. For ensemble streamflow forecasts to add value to risk-based decisions, the forecasts need to be as accurate as possible and the ensemble spread should reliably quantify remaining uncertainty (i.e. to ensure the spread is not too wide or too narrow).

The production of ensemble streamflow forecasts depends on many sources of data and involves multiple steps, resulting in many potential sources of errors and uncertainty. Simple conceptual hydrological models can be used to represent the process of transforming precipitation to streamflow. Hydrological models are calibrated using observed precipitation and potential evapotranspiration as forcings and adjusting model parameters to ensure that simulated streamflow closely matches observations. A streamflow forecast is then generated by initializing the calibrated hydrological model with observed precipitation and evapotranspiration, and then forcing the hydrological model with weather forecasts derived from numerical weather prediction (NWP) models. The hydrological and NWP models are simplified representations of real-world processes and therefore result in prediction errors. Imperfect observational data introduce errors into model calibrations and the model initial conditions used to generate forecasts. In combination, these errors mean that streamflow forecasts are fundamentally uncertain.

In this presentation we will describe methods to generate reliable ensemble streamflow forecasts that combine statistical techniques and process-based models. Sub-daily precipitation for sub-catchments, used to calibrate and initialize hydrological models, is generated using methods that explicitly describe uncertainties arising from a sparse network of rain gauges and missing observations in gauge records. Numerical weather predictions are post-processed using statistical methods (Robertson et al. 2013; Shrestha et al. 2015) to generate sub-catchment precipitation forecasts with minimal bias and reliable uncertainty estimates. Uncertainties in hydrological model predictions are handled with a staged hydrological error model that reduces errors and quantifies remaining uncertainty (Li et al. 2016). For both rainfall and streamflow, the methods handle heteroscedasticity with data transformation. Zero values in rainfalls and ephemeral streamflow records are difficult to handle with conventional statistical methods, and
we show that data censoring is a highly effective method for handling data with zeros. The presentation will conclude by highlighting opportunities to improve forecast accuracy and reduce uncertainty.

References


ASSESSING THE QUALITY OF ENSEMBLE NWP RAINFALL FORECASTS FOR STREAMFLOW FORECASTING

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The Bureau of Meteorology currently provides a deterministic 7-day streamflow forecast (SDF) service that delivers likely daily river flow volumes in the coming week to the public at 88 catchments across Australia. In order to provide a greater forecast confidence and reliability, the Bureau is planning to develop its first national ensemble 7-day streamflow forecast service by 2019. Ensemble streamflow forecasts will be generated using Bureau’s Numerical Weather Prediction (NWP) rainfall forecast products, which consist of: (i) the Australian Community Climate and Earth-System Simulator – Global Ensembles (ACCESS-GE, 24 ensembles), (ii) Poor Man's Ensemble (PME, ensemble mean), and (iii) European Centre for Medium-Range Weather Forecasts (ECMWF, 50 ensembles) of the atmospheric model. It is intended to use Bureau's seamless rainfall forecasts when they are available operationally. ACCESS-GE and ECMWF rainfall forecasts are post-processed using a Bayesian joint probability model (Robertson et al., 2013) to correct biases and quantify uncertainty. Thirty catchments (Figure 1) in the current SDF service were selected for evaluation of the ensemble rainfall and streamflow forecasts. The accuracy and reliability of rainfall forecasts are evaluated at the catchment scale. Raw and post-processed rainfall forecasts are assessed separately to identify the value of post processing. Evaluation results of the quality of forecast rainfall for hydrological applications are presented with uncertainty estimates. Characteristics of the three different numerical weather prediction (NWP) rainfall products, and the value of rainfall post-processing are discussed and recommendations are given for the development of the operational ensemble forecast system.
Figure 1. Catchment locations of this study. Catchments of the current SDF service (public and registered users only) are also present.

References

AQFX – A SHORT TERM SMOKE FORECASTING TOOL FOR PRESCRIBED BURN MANAGEMENT

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Prescribed burning is a tool which is used to reduce the mass of understory vegetation and detritus within fire prone landscapes with the goal of reducing the risk of large scale bushfires. An unwanted side effect of prescribed burning is smoke pollution, of which a major component is fine particles. It is now well known that exposure to PM2.5 (particles with a diameter of less than 2.5 microns) can lead to health responses in a population ranging from coughing and wheezing and, for some individuals, increased risks of mortality from cardiovascular and respiratory diseases or stroke. There is currently no known lower threshold of PM2.5 for safe population exposure.

In south-eastern Australia prescribed burning is predominantly undertaken in autumn and early winter during conditions of light winds, moderate temperatures and humidity (preferably persisting for a few days) where the fire ignition and combustion characteristics each burn can be well managed. However such conditions are also conducive to the build-up and persistence of air pollution, with smoke from prescribed burning potentially adding to existing air pollution from domestic wood combustion, motor vehicles, shipping and other significant sources of pollution.

So the challenge for land use managers is achieving a reduction in population risk of harm due to bushfires while minimising the associated increase in population risk due to smoke exposure from the use of prescribed burning. Quantitative forecasts based on smoke transport models can help address this challenge by providing advance warning to affected populations and/or managing the timing of a schedule of prescribed burns.

In this presentation we will provide an overview of AQFx, a three-tiered fire risk and smoke forecasting framework which has been developed for the Victorian Department of Environment, Land, Water and Planning. The framework provides 10-day ensemble forecasts of fire weather and 24-72 hour forecasts of air pollution loadings across Australia. A next-day forecast of planned burn smoke impacts utilises a tagged-tracer inversion modelling approach which enables a complete source-receptor attribution to be undertaken. Fig. 1 shows the AQFx web portal which is used by DELWP as part of their daily operations.
Figure 1. The AQFx web portal, showing how the components of the 3-tiered system can all be accessed from this site. The concentration contours are for a forecast of PM2.5 concentrations downwind of a series of vegetation burns within Victoria.
THUNDERSTORM ASTHMA – CHALLENGES IN PREDICTING A RARE EVENT

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Introduction

On the evening of Monday 21 November 2016, Melbourne and Geelong experienced an epidemic thunderstorm asthma event which was unprecedented in terms of scale and severity compared with previous known events in Australia and globally. It resulted in thousands of people developing breathing difficulties in a very short period of time, creating extreme demand across the health service system. Ten deaths are potentially linked to the event and are being considered by the coroners court (OCHO, 2017).

The State of Victoria responded quickly, commissioning reviews of the health impacts (OCHO, 2017), the response of the emergency management and health sectors (IGEM, 2017) and the body of literature related to thunderstorm asthma and public health advice (Davies et al., 2017). To accompany increases in community education and emergency response planning, the Victorian Department of Health and Human Services (DHHS), the Bureau of Meteorology, CSIRO and university partners are working together to develop and pilot a forecasting system for epidemic thunderstorm asthma (ETSA) to assist in alerting the community and the health and emergency response sectors.

This paper describes the development of the pilot ETSA forecasting system that was launched on 1 October 2017 and will be improved in the next three years through targeted research.

What causes thunderstorm asthma?

Davies et al. (2017) provide an excellent review of what is currently known about thunderstorm asthma. Briefly, thunderstorm asthma is a relatively rare event that requires the confluence of three factors: (1) presence of aeroallergens such as pollen, fungal spores, or particulate matter (ryegrass pollen is believed to be the primary source in southeastern Australia); (2) weather conditions such as thunderstorm outflows that pick up the allergens, concentrate them near ground level and may also contribute to their rupture; and (3) exposure of sensitive individuals who typically suffer from hayfever with uncontrolled or undiagnosed asthma (Fig. 1).
The role of the thunderstorm in producing ETSA is not well understood. Marks et al. (2001) theorized that pollen grains may be entrained into thunderstorm updrafts where they are moistened and ruptured by contact with raindrops, and subsequently transported downward in the thunderstorm downdraft and concentrated in the gust front. Lightning has been implicated in some overseas studies, although the mechanism is not clear.

Figure 1. Hypothesised mechanism for thunderstorm asthma (after Marks et al. 2001).

Not all thunderstorms during pollen season lead to thunderstorm asthma, nor are all heightened asthma events associated with thunderstorms. Our recent work matching weather conditions during pollen season to significant increases in asthma-related hospital presentations (4.5 standard deviations over the expected values at each hospital, which we abbreviate "TSA days") implicated gusty winds associated with convergence lines that were not always associated with thunderstorm outflows. We believe that the organisation of the 21 Nov 2016 thunderstorms into a squall line may have served to concentrate the aeroallergens to a greater degree by limiting the ability of the gust front to spread laterally.

**Development of a pilot forecast service**

Given the limited understanding of the phenomenon of thunderstorm asthma and the consequent uncertainties inherent in establishing an operational forecasting system, we are trialling a pilot early warning system over the next three years. Improvements will be made as understanding improves. The Bureau's role is to analyse the ETSA risk and deliver forecasts to DHHS where they are linked to associated education, monitoring and response systems. Forecasts run from October through December, the typical Victorian grass pollen season, and can be accessed via the Vic Emergency App or [www.emergency.vic.gov.au/prepare](http://www.emergency.vic.gov.au/prepare).

The forecasts are based on a decision matrix comprising (a) statistical forecasts of pollen within nine public weather forecast districts in Victoria, and (b) forecaster assessed likelihood of thunderstorms with strong wind gusts (Fig. 2). This approach was necessarily simple because of the tight time frame to deliver forecasts starting 1 October 2017, and because the relevant
mechanisms and actual likelihoods of events are still poorly understood. Note that this interpretation of "risk" is relative and does not account for vulnerability and exposure.

<table>
<thead>
<tr>
<th>Epidemic Thunderstorm Asthma Decision Matrix 2017-18</th>
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<tbody>
<tr>
<td><strong>Weather factors affecting at least one third of a district</strong></td>
</tr>
<tr>
<td>&gt;30% (Likely) chance of thunderstorms causing gusts &gt;= 50kts (squall line potential adds to risk)</td>
</tr>
<tr>
<td>Low</td>
</tr>
<tr>
<td>&gt;30% (Likely) chance of thunderstorms with 35 &lt; gust &lt; 50kts or ICON (measure of convergence) &gt;=20</td>
</tr>
<tr>
<td>Low</td>
</tr>
<tr>
<td>&lt;30% (Chance) or nil chance of thunderstorms or ICON (measure of convergence) &lt;20</td>
</tr>
<tr>
<td>Low</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>District Pollen Forecast (m^3)</th>
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</thead>
<tbody>
<tr>
<td>Low (0-19)</td>
</tr>
</tbody>
</table>

Figure 2. Decision matrix for forecasts of epidemic thunderstorm asthma risk.

Both false alarms and missed events are of concern to DHHS and the community. To estimate the accuracy of ETSA forecasts, the Bureau's severe thunderstorm wind warnings during October-December 2007-2015 were matched to 11 suspected thunderstorm asthma events based on large numbers of asthma presentations to hospitals in the greater Melbourne region. If the daily Melbourne University pollen count was recorded as 50 or above (thus using the pollen reading as a perfect forecast) and this coincided with a forecast of damaging winds covering at least one third of the Central forecast district it was assessed that the ETSA risk would have been rated as High. The verification of hindcasts of "high risk" is shown in Fig. 3.

<table>
<thead>
<tr>
<th>Day 1 obs Day 0 obs</th>
<th>Day 0 forecast</th>
<th>Day 0 warning</th>
<th>Day 0 cell warning Melb</th>
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<tr>
<td>Day 1 forecast</td>
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<td>Day 0 obs Melb</td>
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<td>6 716</td>
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</table>

Figure 3. Verification of ETSA hindcasts of TSA high risk for Central district for 2007-2015 using "perfect pollen" input, for (from left to right) day 1 forecasts, day 0 forecasts made that morning, day 0 real-time warnings, and real-time cell-based warnings of severe thunderstorm winds for Melbourne.

These results illustrate the difficulty in predicting a high risk of thunderstorm asthma, even when the pollen concentration is known. Two thirds of forecasts and warnings for high risk of ETSA would have been false alarms, which may be acceptable for rare extreme events. However, day 1 forecasts would have predicted high risk for two out of 11 events, and day 0 forecasts would have correctly predicted high risk slightly less than half the time. It was not possible to verify hindcasts of moderate risk as the Bureau does not issue thunderstorm wind warnings for gusts less than 50 kts (90 km/hr).
To better understand airborne pollen sources five new pollen monitoring sites have been established in country Victoria to augment the existing urban sites in Parkville, Burwood, and Geelong. The University of Melbourne has purchased and installed Burkard pollen traps at campuses in Dookie, Hamilton, Bendigo, Creswick and Churchill, and provided training on grass pollen counting. Measurements of grass and total pollen concentration (grains per m$^3$) are made each morning and will provide input for forecasting as well as data for verifying the accuracy of pollen forecasts. A daily grass pollen surveillance standard established for ETSA forecasts will help assure the quality of the pollen counts.

A simple statistical model for airborne grass pollen forecasts in southeast Australia has been developed (Silver, 2017). It relates grass pollen concentration to a number of predictor variables (position in the pollen season, pasture grass fraction in the upwind direction, daily rainfall, and daily mean temperature and relative humidity). The position in the pollen season is estimated from the time series of Enhanced Vegetation Index (EVI) data from the MODIS satellite. The pollen forecasts were tuned and tested using Melbourne pollen observations from 1991-2016. Verification against independent observations from Wagga Wagga and Canberra suggest that the form of the model is valid, but bias correction of the forecasts using the new pollen monitoring data will be necessary to provide more accurate forecasts across Victoria.

**Research to improve thunderstorm asthma forecasts**

In parallel with the pilot forecast service we are embarking on a three year program of research to test improvements in thunderstorm forecasting and develop a physical model of pollen emission and dispersion that will improve the pilot ETSA forecast service.

The Bureau currently applies empirical schemes to numerical weather prediction (NWP) output to identify environments conducive to strong thunderstorm downdrafts and gusty outflows. New higher resolution (1.5 km) modelling allows the explicit representation of thunderstorm processes, requiring new ways of interpreting model output. This is an active area of research in the Bureau as well as internationally, and will be leveraged to improve ETSA forecasting. We will investigate the ability of recent and future advances in NWP to improve the prediction of thunderstorm outflows, focusing on events where thunderstorm asthma has occurred or is suspected (TSA days). Improvements in thunderstorm nowcasting using dual-polarimetric radar and Himawari-8/9 satellite data will also be assessed.

The key components of physical pollen forecasting for ETSA include productivity of grassland cover, grass phenology and pollen release, meteorological data, rupture of pollen grains and delivery of pollen allergens to populated areas (Davies et al., 2017). The vegetation state (phenology) can be detected from satellite using EVI, which is sensitive to changes in canopy greenness and structure, and Normalized Difference Vegetation Index (NDVI), which is sensitive to canopy PAR absorption. The temporal evolution of these indices is used to measure the timing and amplitude of different phases in the growing season that relate to pollen production. To improve the temporal resolution of vegetation state we will develop an EVI based on Himawari-8/9 data incorporating necessary atmospheric corrections, and validate it against MODIS EVI values and surface observations of grass phenology made using automated
time-lapse digital photography (phenocams) deployed by University of Technology Sydney at five Bureau of Meteorology observing sites in Victoria.

The rate of pollen emission from rye grass and other vegetation depends on the vegetation state and meteorological factors such as temperature, humidity, wind, and turbulence. We will improve the prototype pollen emissions model developed at the University of Melbourne which produces spatially and temporally varying plumes emitting from local and regional vegetation sources. Because estimating the amount of pollen at source is highly uncertain, pollen forecasts will be scaled according to recent pollen observations.

Physically-based transport and dispersion modelling represents more complex atmospheric flows, stability effects, and dry and wet deposition, and therefore should produce more accurate pollen forecasts than simpler statistical models. The Bureau’s new smoke and air quality forecast system (AQFx), which is based on ACCESS NWP and CSIRO’s Chemical Transport Model, will be extended to produce daily forecasts of pollen concentration across the state using pollen input from the pollen emissions model. We will test the pollen dispersion forecasts by running the model for past pollen seasons and verifying against pollen data from Melbourne, Burwood, Geelong, Canberra, Wagga Wagga and Sydney, also comparing to statistical and persistence forecasts. Ensemble approaches will also be tested. Whilst this project focuses necessarily on thunderstorm asthma risk in Victoria, the forecasting system for pollen exposure developed herein has potential to be extended nationally to address needs of allergy and asthma patients in other states.

Finally, we will develop a parameterization for bursting pollen in a moist environment, building on laboratory studies that have investigated pollen rupture mechanisms. We will run the modelling system with and without the rupture parameterization on TSA and non-TSA days and assess whether it gave additional useful predictive information. Given the small number of TSA days, establishing statistical significance will be challenging and it is likely that results will be indicative at best.

**Conclusions**

Thunderstorm asthma is a rare but high impact event that is very dangerous to human health, and about which there are many questions. Predicting the occurrence of epidemic thunderstorm asthma presents an enormous challenge, and it is likely that in order to avoid the consequences of a missed event there will be many forecasts that are false alarms. This is a reality of severe weather prediction which most people accept in order to receive warnings, but has discouraged the issuing of thunderstorm asthma forecasts elsewhere (e.g. Newson et al. 1998). ETSA forecasts are one component of a multi-faceted response to the November 2016 epidemic thunderstorm asthma event. Greater community awareness of the springtime thunderstorm asthma hazard will lead to individuals being better prepared with appropriate medication use and avoidance behaviours, the health sector better able to provide advice, and first responders ready to take action when ETSA events occur.
References


THE WAROONA FIRE: EXTREME FIRE BEHAVIOUR AND SIMULATIONS WITH A COUPLED FIRE-ATMOSPHERE MODEL

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The Waroona fire burnt over 68,000 ha and destroyed more than 160 homes in southwest Western Australia in January 2016. On the second evening of the fire, there were two fatalities when the fire made an unexpected run and produced a destructive ember storm over the town of Yarloop.

During the first two days of the fire, there were four episodes of extreme fire behaviour. Two separate pyrocumulonimbus events developed; both produced anomalously fast runs in the prevailing winds, with one pyrocumulonimbus igniting new fires downwind. The other pyrocumulonimbus event occurred at a time that is outside the normal diurnal timing of thunderstorms. Two evening ember storms occurred; the first impacted the town of Waroona and the second caused the devastation at Yarloop. The ember storms were driven by fire plumes interacting with local downslope winds; resulting in a turbulent horizontal transport mechanism for lofting and transport of numerous firebrands.

The processes that occurred at the Waroona fire were driven by three dimensional fire-atmosphere interactions. The detail of such processes can be examined using a coupled fire-atmosphere model.

The Australian Community Climate and Earth-System Simulator (ACCESS) Numerical Weather Prediction model has been coupled to a fire spread prediction model. The coupled model can be used to simulate large fires with full coupling to the atmosphere. The code has been developed and tested by Monash University (publications in preparation). The fire spread code is implemented by a level set solver and includes a number of fire spread formulae including McArthur, Rothermel and Vesta. SRTM topography is used and fuel maps can be included as available. The ACCESS model can be run at resolutions of hundreds of meters and the required resolution to resolve dynamic feedback processes will be explored as the project evolves.

This paper will describe key features of the extreme fire behaviour of the Waroona fire, introduce the coupled fire-atmosphere model ACCESS-Fire and report on progress simulating the Waroona event with the coupled model.
Figure 1. Pyrocumulonimbus above the Waroona fire. Image provided by Neil Bennet, Bureau of Meteorology.
BUSHFIRE PREDICTIVE SERVICES

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Introduction

We discuss two recent projects conducted by the Bureau of Meteorology (BoM) at the request of, and in partnership with, Australian fire agencies. A fire simulator evaluation project reviewed the performance of fire behaviour simulation software commonly used in Australia, focusing on the needs of a variety of user groups, and was completed in June 2017. The second project formally commenced in July 2017, and has developed a prototype National Fire Danger Rating System for Australia, the outputs of which are being evaluated by fire managers around the country during the 2017-18 southern fire season.

Fire simulator evaluation

Fire simulators predict the surface spread of fire across a landscape (Sullivan 2009). In Australia, several simulators have been used in recent years by fire agencies to assist in operational decision-making and planning for fuel reduction activities. However, the guidance provided by simulators is recognized as imperfect (Alexander & Cruz 2013, Finney 2000, Kelso et al. 2015). In collaboration with Australian fire agencies, BoM evaluated the performance of the four simulators used, or that potentially will be used, by fire agencies: Phoenix (Tolhurst et al. 2008), Australis (Johnston et al. 2008), Spark (Hilton et al. 2015) and Prometheus (Tymstra et al. 2010). Several versions of Phoenix and Spark were available to evaluate.

The project adopted a user-focused approach. An initial user-consultation stage resulted in a set of questions about simulator performance that the evaluation aimed to answer. The user questions were mapped to evaluation metrics and means to display the evaluation metrics to assist in analysis of results. Considerable effort was required to select ten fire events that represented a range of environments and weather conditions, and to standardise input data for the analysis. Inputs consisted of weather data from the Australian Digital Forecast Database (ADFD), together with fuel and topography datasets from fire agencies. Observed fire boundaries were the only consistently available fire behaviour data, against which simulator output boundaries were evaluated for specific corresponding times.

Where possible, input parameters were perturbed to assess simulator sensitivity to small variations (and, by implication, inaccuracies in inputs). In particular, weather inputs were perturbed according to an analysis of a climatology of differences between ADFD gridded
forecasts for fire locations, and observations at corresponding times from nearby automatic weather stations.

Several objective spatial evaluation metrics were selected to assess simulator performance, with a summary metric, indicating overall performance, being threat score (Jolliffe & Stephenson 2011). Threat score ranges from 0 (poor) to 1 (good). Both simulator accuracy and sensitivity to variations in initial conditions were important to assess, and modified Hinton diagrams were used to display evaluation output (Figure 1). In the example in Figure 1, accuracy is denoted by colour, with pink poorer and green better accuracy, while sensitivity is denoted by size, with less sensitivity represented by small boxes and large boxes higher sensitivity. The range of threat scores is indicated by the colour map at the top of the diagram, with the best (Australis, in this example) scoring 0.52 and the worst (Spark Vesta 0.8.0) 0.11.

A number of other methods for displaying the evaluation output were also used, to highlight different aspects of the findings. In particular, performance diagrams illustrated the complete range of simulator output. In Figure 2, the distribution of Spark simulators across a performance diagram is displayed. In this plot, Probability of Detection is displayed on the vertical axis, and Success Ratio on the horizontal, with threat score displayed on diagonal isolines. Good performance is represented by simulator instances in the top right, and poor performance in the bottom left. These provide a useful summary of overall simulator performance.

The fire simulator evaluation project delivered a number of key outcomes, available with the full report (Faggian et al. 2017). Among the outcomes are the findings that no one fire simulator is superior, or even adequate – more development is required, and that development needs quality fire behaviour data as input. Given the variability in simulator input and performance, simulators should be run in an ensemble mode, to account for possible spread in outputs. Much work was needed to collect and standardise data for the project, and the data from this project can now form the seed of what should be a national library of fire events suitable for future fire simulator development and refinement.
National Fire Danger Rating System Prototype

The McArthur fire danger ratings system, used over much of Australia, has been employed by Australian fire agencies since the 1960’s. The Bureau of Meteorology has calculated fire danger indices from forecast weather parameters throughout that time, generating fire danger ratings and public warnings from the indices, based on agency advice, for land managers and for the public.

The current system is widely recognised as requiring updating, to:

- include fuels other than dry eucalypt forest and grassland;
- better include progress in fire and atmospheric science over recent decades, and
- produce ratings that can be directly related to measurable fire characteristics, allowing verification of the system.

Momentum has increased in recent years to develop a prototype updated system. Two years ago, NSW Rural Fire Service (RFS) trialled a system for NSW only. Now, RFS and BoM are working in partnership to develop a prototype, using similar fire indices to those in the initial trial, across the whole of Australia, and RFS is co-ordinating with fire agency staff around Australia to verify the performance of the new system’s predictions this summer. The project will run until July 2018, with evaluation and documentation occurring following the completion of observations in March.

The project generates fire danger indices from eight published fire behaviour models, covering a range of fuel types representative of those found across Australia. The fuel map is the first standardised, national map available, and has potential use across a range of other applications. It is based on the best available state agency maps, and is at 1.5 km resolution across its domain. The individual fire behaviour models are a standardised reference implementation of all models sufficiently developed to be used in operations.

A modular approach to the calculation of the indices means that updates and refinements can be added, as research is published and new knowledge comes to light – a process that has already occurred in the prototype.

Ratings are based on anticipated observable fire behaviour, on a scale from 1 (insignificant) to 6 (potentially catastrophic), but clearly distinguishable from the current McArthur rating system, to avoid confusion. For each fuel type, and level of fire activity, expected behaviours are
documented. This enables fire managers across Australia to document the performance of the system, and permit an evaluation of the prototype.

Ratings (and indices) are calculated from ADFD hourly grids on a fire district basis, with the daily rating assigned as that corresponding to the 90th percentile of the daily maximum value for each grid cell in the district. This is the same procedure used to generate operational fire danger ratings grids currently. Figure 4 shows a sample of the output rating map for Australia. In addition to ratings, “red flags” are calculated, based on Continuous Haines Index (Mills and McCaw 2010), Wind Change Danger Index (Huang and Mills 2006) and McArthur spotting potential (McArthur 1967), highlighting potential for increased fire activity. Potential demonstration products may be displayed during the course of the project from other ongoing projects, including JASMIN (Dharssi and Vinodkumar, 2017) and fire weather products from the National Operations Centre Extreme Weather Desk.

During the course of the project, the first tranche of Australian regional reanalysis data (Jakob et al. 2017) will become available for use, covering the period 2010-2015. NFDRS calculations will be performed on this dataset, to provide an initial climatology of the rating system, and to inform ratings thresholds for future trials and eventual operational implementation.

A National Fire Danger Rating System has been an aspiration for Australian emergency management agencies, including the Bureau of Meteorology, for many years. This project is providing a clear pathway to the implementation of such a system, and is an excellent example of the value of interagency collaboration.

References


Figure 4. Fire danger rating map for Australia.


TRANSFORMING SATELLITE DATA TO PRODUCTS IN THE ERA OF BIG DATA

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Introduction

Meteorological satellites are a critical component of the earth observation system, providing valuable information on phenomena ranging from weather to volcanic eruptions. In recent years, meteorological satellite capabilities have been significantly upgraded. For instance, the National Oceanic and Atmospheric Administration (NOAA) and the Japanese Meteorological Agency (JMA) recently deployed new geostationary satellites that each produces over 100 billion earth observations each day, which is about 100 times greater than the previous generation of satellites (Figure 1, left panel). Further, as additional “next generation” satellites are deployed in the coming years, geostationary meteorological satellites, alone, will generate over 1 trillion earth observations per day (Figure 1, right panel). While “next generation” satellites, such as GOES-16¹, have already had a significant impact on decision-making, the very large data volume is challenging to fully exploit. In traditional satellite product generation, radiometric data from a single meteorological satellite are transformed into one or more geophysical parameters that have the same pixel dimensions as the input satellite measurements (with a few exceptions). As such, the traditional product generation paradigm does little to reduce data volumes. Further, the end user’s are generally responsible for extracting relevant information from traditional satellite products (referred to as Level 2 or L2 for short). We propose a modified paradigm for generating satellite products, where the end products are the result of distilling very large volumes of satellite data, from all relevant sensors, and non-satellite data into much smaller volumes of information that is directly relevant to decision making. As described in the remainder of this abstract, the modified satellite product concept, referred to as L2+, has been successfully demonstrated for volcanic cloud, severe weather, and fog/low stratus applications.
**Volcanic Ash Clouds**

Volcanic ash clouds are a major aviation hazard (e.g. Lechner et al., 2017). Thus, timely and accurate information on airborne volcanic ash is critical. Manual analysis of satellite imagery is the primary tool used by Volcanic Ash Advisory Centers (VAAC’s) for identifying, tracking, and characterizing volcanic clouds. While manual analysis of satellite imagery will always be valuable, automated detection, tracking, and characterization of volcanic ash clouds are also needed to ensure full utilization of satellite data for volcanic cloud applications, as forecasters cannot manually examine every satellite image in near real-time. In effort to better utilize satellite data for volcanic cloud applications, NOAA, in collaboration with the Cooperative Institute for Meteorological Satellite Studies (CIMSS), has developed the VOLcanic Cloud Analysis Toolkit (VOLCAT). VOLCAT ingests large volumes of data, from many different satellites, to automatically detect volcanic eruptions and send SMS and/or email alerts to relevant users when an eruption is detected (see Figure 2). VOLCAT also automatically tracks and characterizes volcanic ash clouds in an effort to improve volcanic ash cloud forecasts (e.g. Crawford et al., 2016; Chai et al., 2017). The VOLCAT algorithms utilize unique spectral, spatial, and temporal metrics within a supervised learning framework (Pavolonis, 2010; Pavolonis et al., 2013; Pavolonis et al., 2015a; Pavolonis et al., 2015b; Pavolonis et al., 2017). VOLCAT is a proven tool for distilling very large volumes of satellite data into actionable information.
Severe Weather

The L2+ paradigm also readily accommodates the use of satellite data in combination with non-satellite measurements. The NOAA/CIMSS ProbSevere (“probability of severe”) model (Cintineo et al., 2013; Cintineo et al., 2014; Cintineo et al., 2017) is a multi data source L2+ product. Timely and accurate severe thunderstorm and tornado warnings are critical for protecting life and property. The ProbSevere model was developed with the goal of improving the timeliness and accuracy of severe weather warning operations. ProbSevere utilizes Numerical Weather Prediction (NWP), geostationary satellite, weather radar, and ground based lightning data to estimate the probability that a developing thunderstorm will produce severe (damaging) weather up to 90 minutes in the future. In the median, ProbSevere provides 14 minutes of additional lead-time compared to traditional radar-only interrogation techniques. ProbSevere guidance is produced on a storm cell basis every 2 minutes (see Figure 3). The storm-cell-based data fusion performed by ProbSevere transforms more than 10 GB of input data per hour into about 6 MB of information. Forecasters in NOAA’s National Weather Service now routinely utilize ProbSevere in severe weather warning operations. The ProbSevere concept can be expanded to other operational problems such as forecasting for aviation and maritime applications.
Figure 12: The overall probability of severe weather (up to 90 minutes in the future), from the ProbSevere model, is displayed as a colored contour around storm cells identifiable in a radar reflectivity image on April 5, 2017 at 10:10 UTC. Magenta colored contours indicate probabilities of 70% or greater. Users of ProbSevere can click on a storm cell of interest to get a text display of the probability of individual severe weather hazards (wind, hail, and tornado) and the metrics used to determine the probability of severe weather. ProbSevere provided more than 10 minutes of additional lead-time, compared to standard radar interrogation techniques, for the storm cell in Alabama (USA) indicated by the white arrow.

**Fog and Low Stratus**

Clouds that have low ceilings and/or result in low surface visibility are a common weather hazard that significantly impacts aviation and ground transportation. In an effort to improve short term fog/low stratus (FLS) forecasting, NOAA, in collaboration with CIMSS, developed a suite of FLS products that are derived from multiple data sources (Gultepe et al., 2014; Pavolonis and Calvert, 2017). The NOAA/CIMSS FLS products merge multiple satellite data sets with NWP to determine the probability that low cloud ceiling and/or low surface visibility conditions are present (see Figure 4). NOAA/NWS forecasters routinely use these FLS products to identify aviation and ground hazards. There have been several instances where the FLS products have reduced the impact of low clouds on airport operations through improved lead-time on the development and dissipation of FLS conditions. The economic impact of the FLS products on aviation is likely significant (Eckert, 2015). In addition, NWS forecasters use
the NOAA/CIMSS FLS products to inform the public when and where fog is present. Consistent with the L2+ paradigm, the FLS products reduce large volumes of data into a smaller volume of information that is directly relevant to decision making.

Figure 13: The probability of Instrument Flight Rule (IFR) conditions due to low cloud ceilings and/or surface visibility is shown for the continental United States and surrounding regions on June 29, 2017 at 08:02:30 UTC. The IFR probability, which was derived from a combination of GOES-16 satellite data and numerical weather prediction data, is routinely used to help manage air traffic and inform the public when and where fog is present.

References


IMPACTS OF SPACE WEATHER ON AVIATION

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Space weather phenomena (solar storms, solar flare radio blackouts, and cosmic radiation) can impact aviation operations, possibly on financial scales comparable to disruptions caused by volcanic ash clouds. Effects include: i) loss of the lower spectrum (or even complete fadeout of the spectrum) of HF radio frequency links on the day-side lasting for few hours during intense solar flares, ii) loss of upper spectrum (or again complete fadeout) of HF radio frequency links lasting for several hours due to reduction of the ionospheric electron densities following the main-phase of some solar storms, iii) satellite navigation position and timing errors associated with ionospheric scintillation-related effects, iv) noisy radio links and GPS navigation errors caused by travelling ionospheric disturbances – these gravity wave activity are sourced by solar disturbances from above and the terrestrial disturbances from below, v) cosmic radiation hazards to humans and avionics particularly for high-latitude and cross-polar flight paths, and vi) an extreme space weather event can cause loss of satellites and/or can induce significant additional currents into long-distance power lines leading to damages to the power transformers – extreme space weather events are very rare and could occur once every 100 to 500 years, but could bring the world back to 1950’s level of technological capability. The purpose of this talk is to highlight some of the research and development work been carried out at Australian Space Weather Services branch in relation to the aforementioned effects. A key focus is to define more objective thresholds for various space weather alerts so that they are of direct relevance to the aviation industry, and therefore, can be easily incorporated into the operational flight planning decisions.
VALUE OF WEATHER KNOWLEDGE FOR AVIATION OPERATIONS

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Weather has a major impact on the aviation industry and managing the effects from meteorological events requires considerable time and effort to ensure the efficient operation of an airline. Here, an 'insider' view of the use of weather applications and data in flight operations and planning from the perspective of Virgin Australia (VA), one of the major airlines of Australia is presented. The presentation will cover some of the ways that meteorology impacts the industry, how VA utilizes weather data and knowledge in its operations and planning and what improvements and innovations to various applications could be made in the future to improve aviation operations.
PREDICTING VOLCANIC ASH DISPERSION FOR AVIATION USING ENSEMBLES

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Introduction

Volcanic ash clouds pose a significant hazard to aircraft and can have a major impact on aviation operations. The Bureau of Meteorology’s Darwin Volcanic Ash Advisory Centre (VAAC) provides an important service for the detection and prediction of volcanic ash in the atmosphere to help the aviation industry with the mitigation of these risks. The VAAC's area of responsibility includes Indonesia and Papua New Guinea, among the most volcanically active regions of the world.

Within the VAAC, the HYSPLIT dispersion model is the primary tool for predicting the near-term positions of volcanic ash clouds. Increasingly, airlines request guidance on the uncertainties associated with warnings for volcanic ash clouds and on quantitative estimates of the concentration of ash to better enable the management of risk. These are both challenging problems.

High-quality forecasts of ash clouds require estimates of the volcanic source term, which includes the total mass eruption rate within the initial eruption and its distribution in space and time for particles of different sizes. Dispersion model forecasts also require input from high-quality Numerical Weather Prediction (NWP) model data and an adequate representation of relevant physical processes within the dispersion model. These aspects have been the subject of research and development activity within the Bureau in support of the aviation industry.

Improving HYSPLIT

Much of the Bureau's R&D effort concerning volcanic ash has been on improvements and extensions of dispersion modelling. One area of focus has been an improved representation of the physical processes within the model, particularly around the removal of ash from the atmosphere. This effort has focused on improving the fall speed parameterization for volcanic ash within the model and the inclusion of more realistic particle size distributions for ash (Dare 2015). Allowing for the removal of ash through sedimentation results in a more realistic simulation compared to simply treating the volcanic cloud as a gas (which is not removed) as was previously the case. Other efforts have investigated the effects of the 'wet deposition' process, the removal of ash by rain and cloud (Dare et al. 2016). This process can remove significant amounts of ash in a brief period and is a particularly important process to consider in the rain-prone regions of the Maritime Continent. As rainfall is often a stochastic process in the
near-equatorial tropics, the inclusion of wet deposition processes accounts for a major source of meteorological variability within the Darwin VAAC area of responsibility.

**Dispersion Ensemble Prediction System**

The work of Dare et al. (2015) has led to the creation of the Dispersion Ensemble Prediction System (DEPS) for volcanic ash. DEPS provides a web-based, demand-driven user interface that defines a set of dispersion model simulations that result in an estimate of the probability that ash amounts exceeding pre-defined thresholds are present within the domain. The probability estimates are derived by initializing HYSPLIT with the Bureau's 24-member global ensemble model (ACCESS-GE), the global deterministic model (ACCESS-G), the regional model (ACCESS-R) and the NOAA GFS simulation to determine the probability estimates. Work is underway to incorporate the ECMWF global simulations into the ensemble. In principle, any NWP data covering the region of interest could be incorporated into the ensemble. Source term parameters for initializing the runs, including the height of the plume, an estimate of the mass eruption rate, the plume type (i.e. column or umbrella cloud) and the particle size distribution within the cloud are customizable, although well-considered default values are also available. The use of multiple NWP realizations of the forecast allows for the effects of meteorological uncertainty to be considered in the volcanic ash forecast. Even relatively small differences between the NWP fields of different ensemble members can result in significant variability in the distribution of the volcanic ash (Figure 1). This example comes from the eruption of Kelut in eastern Java on 13 February 2014 at 1600 UTC (e.g. Lucas and Majewski 2015; Kristiansen et al. 2015). In Figure 1, the mass loading estimates are 2-3 orders of magnitude larger than the satellite derived values, due to uncertainty around the specification of the source term. The resulting probability (Figure 2), defined as the percentage of ensemble members with a mass load in excess of the pre-defined threshold, for this case captures the actual observed distribution of the ash cloud. However, we note that because of the uncertainties with the source term, the actual probabilities are most likely

![Figure 1](image-url)

**Figure 1.** Volcanic ash mass loading (kg m⁻²) fields for three ensemble members from DEPS for the 9-hour forecast for the Kelut eruption of 13 February 2014.
overstated. However, even when uncalibrated, DEPS provides a good indication of the range of possible spread of the ash cloud and should provide useful knowledge to the VAAC and the aviation industry. With the current model setup and the Bureau’s available computing resources, the full ensemble process requires approximately 10-15 minutes to complete. The DEPS system is currently being transitioned into operations at the Bureau; the development version is available for use by the VAAC.

The future of DEPS

Future development of DEPS is centered on incorporating the effects of source term uncertainty into the probabilistic calculations and calibrating the ensemble model. As shown in Figures 1 and 2, uncertainty in the source term and model initialization can result in significant errors in the resulting forecast, particularly in terms of the quantitative estimates.

The basic approach to calibrating the ensemble model after accounting for source term uncertainty is to combine observations of the ash cloud with inverse modelling techniques during a short time window following the commencement of an eruption. The process provides improved estimates of the probability density functions (PDFs) associated with the source terms and meteorological fields, which optimizes the match between the ash clouds modelled by DEPS and the observed (remotely sensed) ash clouds. This is essentially a form of Bayesian inference, with prior PDFs being modified by observations to yield posterior PDFs. The framework for this inverse modelling approach is described by Zidikheri and Potts (2015) and Zidikheri et al. (2017a,b). Initially, the ensemble model calibration will focus on using the spatial boundaries of the ash cloud, as either determined from automated satellite detections or from the manual analysis by the forecaster. This approach optimizes the vertical and horizontal extents of the initial plume, as well as the contribution of the different ensemble members. The latter is especially important in situations where there is significant variance in the wind across ensemble members. Later efforts will focus on optimizing the vertical mass emission profile of the source using the quantitative mass loading retrievals available from satellite data. This step will enable estimates of the mass eruption rate of fine ash, helping to resolve problems associated with the overestimation of ash mass loads noted with Figure 1. Verification of the ensemble forecasts using data from past eruptions shows that incorporating observations into the forecasting process in this manner can significantly improve the 18 and 24-hour forecast skill (M. Zidikheri, manuscript submitted.). These additions to DEPS will be an important step
towards providing reliable ash concentration or mass loading forecasts and their associated uncertainties desired by the aviation industry.

References


METEOROLOGY SUPPORTING THE AVIATION INDUSTRY

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Weather and related environmental phenomena can have a large impact on the aviation industry and to ensure safe and efficient operations of international aviation, weather services for the industry are provided within a framework of standards and recommended practices established by the International Civil Aviation Organization (ICAO) and regulatory requirements at the State level.

Aviation traffic continues to increase and the impact of weather will increase as air traffic management becomes more complex and there is increasing pressure to respond to environmental issues. The address this challenge the ICAO Global Air Navigation Plan (GANP) aims to achieve safety and operational improvements in a globally interoperable, harmonized, environmentally responsible and cost effective air traffic management system. This will be achieved through a series of Aviation System Block Upgrades that build on existing and future capabilities at the global, regional and local level.

To support these efforts the WMO is conducting an Aeronautical Meteorology Scientific Conference in early November 2017 that aims to provide a consolidated scientific evaluation of the present and future meteorological capabilities required to support current and foreseen aeronautical requirements. This includes a commitment to assist ICAO in determining the potential impacts of climate change and variability on aviation. The programme is based around the following areas:

- Science and technology underpinning aeronautical meteorological observations, forecasts, advisories and warnings.
- Integration, use cases, fitness for purpose and service delivery
- Impacts of climate change and variability on aviation and associated science requirements

This presentation will provide a brief overview of the scope and outcomes of the conference.
WEATHER DATA NEEDS FOR THE AUSTRALIAN ENERGY MARKET

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The share of energy supplied by renewable generation based on wind and solar resources in the National Electricity Market (NEM) has increased dramatically in the last decade – 2016 saw over 50% of South Australian electricity demand supplied by renewable generation. The integration of significant penetrations of renewable generation presents unique operational challenges of which AEMO is at the forefront worldwide in having to manage. This presentation will describe the role of AEMO in the NEM as system and market operator, and an analysis of recent case studies showing the impact of the weather on operations, focussing on wind ramp events, solar intermittency due to patchy clouds, solar ramp events due to cloud-fronts, and load response to heat-waves. These case studies will demonstrate the critical impact that weather has on operations in the NEM, and the need for innovative and novel solutions from the meteorology industry to help the energy industry address these challenges.
THE GROWING NEED FOR SOLAR RESOURCE ASSESSMENT AND FORECASTING AND THE CONTRIBUTION OF SATELLITE DATA

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This paper briefly reviews the needs of Australia’s solar energy sector for solar resource data and forecasting, the Bureau of Meteorology’s satellite-based solar data products and work underway to improve them, and opportunities to develop Bureau solar forecasting services.

Need for solar resource data

The contribution of solar energy to electricity production in Australia has risen dramatically in recent years and this is expected to continue (Geoscience Australia and BREE, 2014). Solar power has to date been largely produced by photovoltaic (PV) systems, including a large contribution from rooftop PV, as well as large scale PV plants. Electricity production from concentrating solar thermal technology, which focuses sunlight to heat a working fluid and is most suitable for utility scale plants, has so far been small but is expected to increase.

The solar energy sector needs data on the solar resource for a variety of purposes. Large scale solar power plants require a decade or more of data on solar resource availability before construction to support site selection, project planning and financing. Solar resource data supports planning the electricity grid and research on the integration of solar power into the grid. Solar resource forecasts with horizons of minutes to days support efficient operation of solar power plants, energy storage such as batteries, the grid and the electricity market. For instance, the Australian Energy Market Operator (AEMO) requires solar forecasts of residential PV production to support its roles of balancing supply and demand and operating the National Electricity Market (NEM) that serves eastern Australia. Finally, seasonal forecasts facilitate scheduling of plant maintenance.

The solar resource data required is, in geophysical terms, the downwelling solar irradiance (radiant flux, W m\(^{-2}\)) at the surface for the full solar spectral range (that is, the shortwave range, wavelengths 0.3 \(\mu\)m to 3.0 \(\mu\)m), the time integral of irradiance (radiant exposure, or simply exposure, MJ m\(^{-2}\)) over time intervals ranging from 1 second to 1 day, and climatological averages of exposure over longer intervals. The total irradiance falling on a horizontal surface from the full hemisphere of the sky, known as the Global Horizontal Irradiance (GHI), is usually decomposed into the direct and diffuse components, which come from the Sun's disk and the rest of the sky respectively. The direct component is often expressed as the irradiance on a plane normal to the Sun direction: direct normal irradiance (DNI). GHI suffices to give the radiation incident on a horizontal flat collector such as a horizontal PV panel. The radiation on tilted or sun-tracking PV panels requires knowledge of both DNI and GHI, together with a model of the angular distribution of diffuse radiation across the sky. Concentrating solar applications require knowledge of DNI.
Bureau satellite solar data

The Bureau of Meteorology (the Bureau) currently provides the following suite of historical solar resource data products derived from geostationary satellite data:

- time series of hourly solar irradiance (GHI, DNI);
- time series of daily global horizontal solar exposure;
- monthly and annual climatological means.

All of these products are on a 0.05° geographic grid covering Australian land, and the time series commence at the start of 1990. The daily global horizontal exposure data are updated in near real time, and the hourly irradiance time series (global and direct) are updated in batches every few months. In the current production system, all products are derived from the hourly GHI, which is in turn derived from visible-band images from geostationary satellites using the two-band physical parameterisation of the key interactions of solar radiation with the atmosphere, clouds and surface that was developed by Weymouth and Le Marshall (2001). The satellites used are GMS-4, GMS-5, MTSAT-1R, MTSAT-2 and (currently) Himawari-8, all operated by the Japan Meteorological Agency (JMA), and GOES-9 operated by the US National Oceanic and Atmospheric Administration (NOAA). The DNI is derived from GHI by an empirical separation model that depends primarily on the ratio of surface GHI to top-of-atmosphere GHI and also other variables derived from the GHI data and geometry. The separation model was adapted from the model of Ridley et al. (2010) and fitted to data from the Bureau’s surface radiation network. Data from the surface network are used to reduce biases in the satellite products and assess their uncertainties.

Users can access the satellite solar data products through several channels. The primary distribution is by the Bureau’s climate data services (http://www.bom.gov.au/climate/data-services/solar-information.shtml), with some products available online at no charge and some by request at the cost of distribution. The satellite solar climatologies were one of the first datasets to be made available through the National Environmental Information Infrastructure (NEII, http://www.neii.gov.au) that is hosted by the Bureau. Outside the Bureau, the climatologies and hourly time series to 2014 can be visualized and downloaded through the Australian Renewable Energy Mapping Infrastructure (AREMI, Figure 14). AREMI is a spatial data platform for the Australian energy industry, funded by the Australian Renewable Energy Agency (ARENA). Internationally, the climatology data are available through the Global Atlas for Renewable Energy (http://irena.masdar.ac.ae) that is coordinated by the International Renewable Energy Agency (IRENA).
As an aside, the satellite solar radiation data have applications beyond solar energy. The data are used for:

- agriculture;
- the Bureau’s evaporation estimates at thousands of point locations;
- input to the Bureau’s Australian Water Resource Assessment Landscape (AWRA-L) model, to support the national water assessments;
- building thermal design, including as an input to Australia’s Nationwide House Energy Rating Scheme (NatHERS, [http://www.nathers.gov.au](http://www.nathers.gov.au)).

Also, solar data from the Bureau’s surface network, which is available at 1 minute resolution at a dozen or more sites depending on year, is used by solar energy researchers to understand the impact of rapid transients on power production and grid operation.

**Future development**

The Bureau is evaluating a new scheme for processing satellite data to surface solar radiation which takes advantage of the richer information on cloud properties that is available from the Advanced Himawari Imager (AHI) onboard JMA’s Himawari-8 and -9 satellites compared with earlier geostationary instruments.

Figure 15 outlines the system, which is built around NOAA’s GEOCAT software for estimating the cloud properties from AHI, and the Heliosat-4 scheme (Qu et al., 2016) developed by the Centre for Observation, Impacts and Energy at MINES ParisTech, France. Heliosat-4 inputs satellite-derived cloud microphysical properties and ancillary data on atmospheric composition, surface albedo and observation geometry, and applies radiative transfer modelling by using look up tables derived from extensive runs of a full numeric radiative transfer code.
Compared to the current system, the new system is expected to better model the radiative transfer and also account for effects that are currently neglected including aerosol, dynamic ozone amount and surface altitude. The new scheme also explicitly outputs separate global and direct irradiances. Considering all of these improvements together, the new scheme promises more accurate radiation estimates for each component.

Figure 15. Flowchart of the new satellite solar processing scheme. Turquoise boxes represent data products, while the grey boxes represent software packages.

Besides the updated physical scheme, improvements being considered include:

- Delivery of irradiance time series (GHI and DNI) in near real time.
- Improving temporal resolution from 1 hour to 10 minutes, to match the frequency of AHI images.
- Improving spatial resolution from 0.05° (~5 km) to approximately 2 km (to match the cloud property estimates) or even 1 km (four AHI bands have resolution 1 km or finer). It is likely that the 5 km products would be continued to give dependent users continuity.
- More detailed characterization of uncertainty.

**Solar forecasting**

International experience in solar forecasting uses a range of techniques to span forecast horizons from minutes to days (see the review by Coimbra et al., 2013):

- tracking clouds in ground-based sky images (30 minutes);
- statistical time series modelling (2 hours);
- tracking clouds in satellite images (5 hours);
- numerical weather prediction (NWP) (several days).
Satellite cloud tracking, so-called cloud motion vectors (CMV), has generally been performed by either simple block correlation approaches that generally assume persistence of cloud structure, speed and direction, or by adopting methods from computer vision such as optical flow that acknowledge dynamic cloud structure (Coimbra et al., 2013). Solar forecasting has, as far as the author is aware, made little or no use of the atmospheric motion vector (AMV) techniques or products developed by meteorological agencies. The skill of NWP exceeds that of CMV for forecast horizons longer than approximately 6 hours, and blends of the two have shown better skill than either alone in the cross-over range.

Of the approaches listed, the Bureau currently only provides NWP-based solar forecasts, from the operational ACCESS system. Given the Bureau’s existing in-house supply of near-real-time Himawari-8/9 data and systems to process that data to solar radiation products, there is potential for the Bureau to consider the development of a solar forecasting service based on satellite data, alone or in combination with NWP.

References


OPERATIONAL NWP FORECASTS FOR SOLAR ENERGY OVER AUSTRALIA

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The Australian Community Climate and Earth-System Simulator (ACCESS) system is based on the UK Meteorological Office’s Unified Model and forms the foundation of the Australian Bureau of Meteorology's operational numerical weather prediction (NWP) systems. These comprise of a global model (ACCESS-G), 12 km resolution regional model (ACCESS-R) and 4km resolution city domain models (ACCESS-C). The systems all produce hourly forecasts of direct and diffuse solar energy at the surface which are potentially useful for solar energy forecasts.

The UM’s radiative transfer parameterization scheme is a two-stream approximation which explicitly calculates direct and global solar exposure with the diffuse component determined as the difference between them. The model cloud parametrization is a prognostic mixed phase microphysics scheme with a diagnostic ice cloud fraction. Aerosols are treated using climatology. Due to the calculative complexity of the radiative transfer scheme it is only run hourly during the model forecast process. This means that the cloud properties used to evaluate the surface radiation are effectively fixed for the hour with the added complication of a scheme which modifies the radiation every time step to allow for variation in solar zenith angle over the hour. Hence the surface solar radiation produced is strictly only an approximation relative to exact time evolving radiative transfer calculations with synchronous cloud.

With these limitations in mind, forecast hourly global, direct and diffuse solar exposure fields produced by a number of the operational ACCESS systems have been validated against the sparse high quality measurement network for a number of different periods in the past, with results indicating large compensating biases in direct and diffuse radiation, leading to smaller biases in the global solar exposure (Gregory et al, 2012,2016).

References


METOCEAN IMPACTS ON WOODSIDE OPERATIONS IN THE NORTH WEST SHELF

Grant Elliot

Woodside

Understanding the magnitude of wind and wave impact on operations extends from forecasting the very short time scale (of a few hours) out to much longer time scales (of 7 to 10 days). From a design perspective understanding the potential range of impacts over the next 50 to 100 years requires a different approach to forecasting extremes. This presentation will identify some of the key challenges over both of these timescales, with particular emphasis on some recently observed phenomena together with some new approaches to problem solving.
CLIMATE SCIENCE AND AGRICULTURE; VALUING THE FORECAST AND MAKING THE FORECAST VALUABLE.

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“The importance to the farmer, the horticulturalist, and pastoralist of knowing beforehand the probabilities of dry or wet seasons, and whether the rains will be early or late, or both, has naturally led to a desire for seasonal forecasts. They have them, it is said, in India; why not in Australia?” Sir Charles Todd (1883)

“We are confronted with unprecedented opportunities to tune our agricultural systems in a way that improves their sustainable land use. We have a seasonal forecasting capability. We have started to think through how we can best use the knowledge that season is not a total unknown.” Hammer and Nicholls (1996)

Australian farmers had to wait over a 100 years for Charles Todd’s wish to come to fruition. Since seasonal climate forecasts have been available in the late 1980s, there have been many studies calculating the potential value to agricultural decisions. The majority of these are desktop studies that use simulation models and historical climate records to compare optimum management without a forecast to management with a forecast. The valuation techniques are based on assessing the value of information expressed as shifts in probability distributions. These studies are underpinned by Bayesian revision, Expected Utility Theory and applied Decision Analysis. In a recent review of Australian literature, Parton and Crean found the value of SCF ranged from $2/ha to $66/ha. These values are averages of simulation runs over a hindcast period ranging from 20 to 100 years. In individual years, the value ranges from negative to significantly positive with many years when the value is close to zero.

Studies on the value of forecasts may alert farmers to situations where climate forecasts are more valuable. However, these studies are more likely to be used to assess the benefits of RD&E in the science and application of seasonal climate forecasts. While farmers and their advisers are interested in the studies, they don’t answer the question of what to do this coming season with a given forecast. They may provide a motivation to change, but they don’t provide the next step.

A simple model for change is the the Beckhard-Harris Change Model (DxVxF)>R where D = dissatisfaction, V = Value proposition, F = first or next step and R = resistance. This model acknowledges that there is always resistance to change. Although seasonal climate forecasts are freely available, there is a substantial cost in terms of time to get the latest update and more importantly understand the forecast. To overcome this resistance requires a level of dissatisfaction with the existing situation and confidence in an alternative. Although all farmers are aware of climate risk, not all are highly dissatisfied with their current approaches to managing risk and/or convinced by the value proposition of seasonal climate forecasts. Of the
farmers and agronomists who are wanting to use probabilistic climate information, a barrier might lie in the absence of the next step to take.

In recent times there have been many improvements in the communication of climate information (eg videos from BoM and the Fast Break) understanding the drivers of climate (eg the climate dogs) and translation of climate information into agricultural production (YieldProphet or Ask Bill). There has also been ongoing work on communicating the language and concepts of probabilities. It is our contention that there remains the challenge of how to use probabilistic information in decision making. This sentiment was expressed by an agronomist “that was a nice talk on probabilities, but in the real world farmers have to make a decision.” This statement implies that the only way to use probabilistic climate information is to convert it to a deterministic statement “it will be wet” or a deterministic statement with a qualifier “most models favour a wet spring or we are reasonably confident that it will be a wet spring”. The notion that probabilities can’t be used for decision-making ignores the vast number of important decisions every day that use probabilities in modern finance, medicine, engineering and indeed agriculture.

We are proposing that the some of the basic concepts of decision analysis that are used valuing the forecast can also be used for making the forecast valuable. The steps include the identification of a decision that is climate sensitive and requires a choice between a higher risk, higher return plan that was preferred in a higher rainfall season with a more conservative, lower risk and lower return plan that was preferred in a drier season. Once this information has been elicited from a decision maker, a number of conclusions can be made about the value of the forecast. Examples of decisions include decisions under uncertainty of rainfall and frost.

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TOWARDS SEASONAL PREDICTION APPLICATIONS USING ACCESS-S

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Introduction

In recent years the Bureau of Meteorology (BoM) seasonal climate outlooks have become more skilful, more useful and more popular. However, the present seasonal prediction system, POAMA-2, is low-resolution (250 km) and somewhat dated relative to systems operated by the leading meteorological centres abroad. In early 2018 POAMA will be replaced with a new seasonal forecasting system, ACCESS-S1 (the seasonal prediction version of ACCESS – the Australian Community Climate and Earth-System Simulator, version 1). This will bring seasonal prediction into the national ACCESS modelling framework, which utilises the latest local and overseas developments. ACCESS-S has considerable enhancements compared to POAMA, including higher vertical and horizontal resolution of the component models and state-of-the-art physics parameterisation schemes.

ACCESS-S1 evaluation

One of the most obvious improvements with ACCESS-S will be forecasts with more regional detail. In ACCESS-S the resolution is ~60 km in the Australian region (compared to 250 km in the current system). At this resolution the model can, for example, differentiate between the climates of western and eastern Tasmania and better represents the Great Dividing Range, which plays a key role in the spatial distribution of rainfall. As a result, ACCESS-S1 has markedly reduced biases in the mean state of the climate, both globally and over Australia, compared to POAMA. The ocean model component also has a higher spatial resolution (~25 km) than POAMA (~100-200 km), allowing for better resolution of ocean features such as currents and eddies.

We will describe the multi-week and seasonal performance of ACCESS-S1 based on a 23-year hindcast set (Lim et al. 2016; Hudson et al. 2017a; Hudson et al. 2017b; Marshall and Hendon 2017). ACCESS-S1 better predicts the important drivers of Australian climate variability, namely the El Niño Southern Oscillation, Indian Ocean Dipole, Southern Annular Mode and Madden-Julian Oscillation. There is an overall improvement in the skill of the multi-week forecasts over Australia compared to POAMA. On seasonal timescales the differences between the two systems are generally less marked, although ACCESS-S1 has noticeably improved forecasts over Australia for the austral spring season compared to POAMA, but less skilful forecasts of maximum temperature over eastern Australia for late autumn and winter. Scope for improvement of ACCESS-S in the future will be discussed.
ACCESS-S for applications

ACCESS-S will support a range of applications, including streamflow forecasting, agricultural modelling and marine resources management. These applications will be discussed, as well as future opportunities and new projects. One such project, "Forewarned is forearmed: managing the impacts of extreme climate events", will deliver direct value to farmers through providing forecasts of extremes. The project is supported by funding from the Australian Government Department of Agriculture and Water Resources as part of its Rural R&D for Profit programme. The BoM, working with a number of research partners, will develop and deliver forecasts based on ACCESS-S of the likelihood of climate extremes on multi-week and seasonal timescales – beyond the 7-day weather forecast. Project partners who are agricultural climate and systems analysis researchers, with particular expertise in the dairy, beef, sheep, grains, sugar and wine industries, will use BoM output to determine climate extremes scenarios through appropriate risk management frameworks, farm system models and economic frameworks.

Conclusion

ACCESS-S offers increased potential to meet the rapidly growing demand for multi-week and seasonal prediction services, including those dependent on downstream application modelling. In the coming years, partnerships with stakeholders will become increasingly important in order to unlock the true potential and value of multi-week and seasonal forecasts.

References


CONVERTING CLIMATE SCIENCE INTO CLIMATE SERVICES: A CASE STUDY FROM THE IMPROVED SEASONAL FORECASTING SERVICES PROJECT

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The Improved Seasonal Forecasting Services (ISFS) project has been charged with not only implementing the ACCESS climate model into operations, but also looking at how users convert the probabilistic climate information into real world decisions, and matching this with how we deliver outlooks. Over the past several years the Bureau has looked at how seasonal forecasts have been used in decision making, and how the delivery of the information can be more tailored to assist.

The ISFS project conducted a series of workshops around Australia where they spoke primarily with agricultural users of seasonal forecasting information. A focus was upon not only the quality and understanding of the current service, but also on multi-week information that will be provided by the project. Results showed that there was a surprisingly high degree of misunderstanding of seasonal forecasts and what they can and cannot deliver for users. The correlation between users who did not understand key concepts and users who believed seasonal forecast was of low value was high. This highlighted how carefully crafted information must be when delivered to end users; simply providing maps or raw data is simply not enough. Information needs to be carefully crafted and communicated, and needs to be accompanied by supporting or education materials lest the real value of the underlying data is lost.

Multi-week information was found to be vital to many users, most notably in remote areas where logistics takes longer periods of time, but also in warning of the risk of extreme weather events. Users were less inclined towards ranking based outlooks (e.g. the chance of being above normal or the odds of being in particular terciles) but rather favoured probability of exceedance type outlooks (e.g., the chance of recording 20mm in the next fortnight, or chance of extreme temperature thresholds). However it was found that there were multiple key thresholds that users were interested in rather than just several key numbers, with key thresholds depending upon industry, location and time of year. To achieve such products, calibration of the outlooks is needed. The project is now planning to implement ACCESS-S Probability of Exceedance multi-week outlooks for its phase II release in 2018/19.
SUB-SEASONAL FORECASTS OF TROPICAL CYCLONES IN THE AUSTRALIAN REGION

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The Bureau has used the Predictive Ocean Atmosphere Model for Australia (POAMA) to generate seasonal forecasting products since 2009. However the tropical cyclone seasonal forecasts issued for the Australian tropical cyclone season continue to use a statistical model based on indicators of ENSO. Earlier work by Kay Sheldon and Andrew Charles showed that POAMA hindcasts had limited skill in predicting seasonal tropical cyclone activity in the Australian region, which meant this model has not been used for the official forecast. In this updated study, we assess POAMA’s ability to produce skilful sub-seasonal predictions of tropical cyclone activity in the Australian region. Two storm detection schemes are used to analyse the POAMA forecasts. The first scheme was developed by Kevin Tory at the Bureau and it uses the Okubo-Weiss-Zeta (OWZ) parameter to identify regions conducive to tropical cyclone genesis. The second scheme was developed by Frederic Vitart at ECMWF and is used for their multi-week and seasonal tropical cyclone forecasts. Finally, hindcast results from POAMA's replacement model ACCESS-S for multi-week timescales are also presented.
THE NATIONAL AND INTERNATIONAL DRIVERS SHAPING THE DEVELOPMENT OF BUREAU FUTURE WARNINGS

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The Bureau has a mandate to warn Australian communities of weather and climate events that are likely to cause harm and may result in loss of life and property. This is generally true of all NMHS’s. Our warnings services are generally developed and delivered in a ‘Total Warning System’ context and the messages are typically crafted to describe the current and predicted future state of the environment and then provide some recommended protective actions. Bureau research is generally focused on building skill and precision in understanding and describing the weather elements — the hazard. However, warnings services are evolving. Disaster Risk Reduction priorities — nationally and internationally — have shifted away from mitigating risk by focusing mainly on understanding and responding to the hazard, towards an emphasis on building community resilience by the responding to hazard risk and minimising the consequences of hazard impacts. Australian communities are increasingly demanding that warnings include a forecast of likely hazard impact with an attribution of a level of associated risk. This is a paradigm shift and reflects an international trend towards impact-forecasting and providing risk-based warnings messages. There is now a much greater emphasis on applying skill in communicating uncertainty and understanding and communicating risk. The provision of warnings to the community is increasingly the responsibility of a partnership that encompasses the Bureau, the breadth of the emergency management sector, researchers, social scientists and a range of community stakeholders.

This presentation will provide an over-view of the national and international drivers that are shaping Bureau Future Warnings services and the new partnerships and arrangements that are evolving to underpin this.
MAINTAINING THE RESILIENCE OF THE GREAT BARRIER REEF IN THE 21ST CENTURY: THE IMPORTANCE OF REMOTE SENSING, MODELLING AND FORECASTING TOOLS

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As climate change progresses, extreme weather events are having increasing impacts on the Great Barrier Reef ecosystem, and the industries and communities that depend on it. In the last 15 years cyclones, marine heatwaves, droughts and floods have impacted the entire 344,000km² Marine Park. While global reduction in greenhouse house gas emissions and mitigation of climate change are the most critical actions to improve the outlook for the Reef, local actions to improve the resilience of the system are also essential.

Mapping and modelling exposure to extreme weather are becoming increasingly important in assessing the current condition of the Reef, forecasting its outlook, and adapting Marine Park management to improve the resilience of the system.

Advance planning for incident responses, as well as proactive communication with stakeholders, rely on good forecasting. We rely heavily on cyclone and thermal anomaly forecasts (POAMA/ACCESS-S) for these purposes.

Given the enormous scale of the Reef ecosystem, our ability to monitor impacts and condition in a timely and spatially comprehensive way is limited. Increasingly, we rely on mapping exposure to pressures such as thermal stress and damaging waves as a proxy for contemporary Reef condition. Products such as cyclone tracks and heat stress maps (Reef Temp) are critical in effectively mapping this exposure.

One of the major initiatives of the Reef 2050 Plan is the development of the ‘Reef Integrated Monitoring and Reporting Program’. This will bring together forecasting, mapping, monitoring, modelling and reporting tools into an integrated framework that supports resilience-based management into the future. Tools around weather and climate will be critical components of this program.
SEASONAL FORECASTING FOR MARINE RESOURCE USERS – LESSONS FROM 10 YEARS OF DELIVERY

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Introduction

The production of marine protein from fishing and aquaculture is influenced by environmental conditions. Ocean temperature, for example, can change the growth rate of cultured animals, or the distribution of wild stocks. In turn these impacts may require changes in fishing or farming practices. In addition to short-term environmental fluctuations, long-term climate-related trends are also resulting in new conditions, necessitating adjustment in fishing, farming and management approaches. Longer-term climate forecasts, however, are seen as less relevant by many in the seafood sector owing to more immediate concerns (Hobday et al. 2016). Seasonal forecasts provide insight into upcoming environmental conditions, and thus allow improved decision making. Forecasts based on dynamic ocean models are now possible and offer improved performance relative to statistical forecasts, particularly given baseline shifts in the environment as a result of climate change (Salinger et al 2016; Tommasi et al. 2017).

Seasonal forecasting is being used in marine farming and fishing operations in Australia, including wild tuna (Hobday et al. 2011; Eveson et al. 2015) and dolphinfish (Brodie et. Al. 2017); and farmed salmon (Spillman and Hobday 2014) and prawns (Spillman et al 2014), to reduce uncertainty and manage business risks (Figure 1). Forecast variables include water temperature, rainfall and air temperature, and are considered useful up to approximately 4 months into the future, depending on the region and season of interest. Species-specific habitat forecasts can also be made by combining these environment forecasts with biological habitat preference data.
Engaging with stakeholders

We’ve found that stakeholder engagement, while time consuming, is critical to long-term use of forecasts. Embedding an end user into the project team developing an application enables trusted two-way communication between the “science” and the “user”. Discussions about need, decision time scales and availability of verification data from the user also build trust and increases likelihood of uptake (Figure 2). Development follows a pretty standard approach in our projects, with skill assessment and forecast product development. Implementation is usually under-budgeted, however, ongoing relationships can be maintained with low overhead if the embedded end user remains engaged. This also provides ongoing opportunity for feedback and improvement to the forecast system.
Conclusion

Partnerships between model developers, model users, and stakeholders are complex and time consuming to develop. Many decisions are made with leadtimes compatible with the use of seasonal forecasts. Seasonal forecasts are useful when a range of options are available for implementation in response to the forecasts. The use of seasonal forecasts in supporting effective marine management represents a useful stepping stone to improved decision making and industry resilience at longer timescales (Hobday et al. 2016; Hobday et al. in review). Development of new systems based on ACCESS-S offer exciting opportunities to explore delivery to existing and coastal users, as downscaling techniques (Vanhatalo et al. 2016) remain computationally intensive.

References


EXTENDING AUSWAVE TO THE NEARSHORE

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1. Introduction

Beach wave height is currently not part of the Bureau of Meteorology’s (the Bureau’s) operational AUSWAVE forecast system. The main limitation is that the spatial resolution of the operational system (approximately 10km) is inadequate to resolve physical details of a particular beach location (i.e. nearshore bathymetry, orientation of coastline, etc.). There are a number of approaches to transform wave information from an offshore location to nearshore. For this study we tested the following two approaches:

- Neural networks
- Spectral modelling

Byron Bay was selected for this study primarily because nearshore visual observations over a period of 3.5 years were available and provided by Surf Life Saving New South Wales. This dataset was used to train and validate our two approaches.

2. Neural Networks

Artificial neural networks can be utilized as a proxy for many physical models (e.g. Krasnopolsky et al. 2007). They are frequently used as a classification tool to map one set of input parameters to a set of output parameters. Neural networks have previously been used for nearshore wave transformation, e.g. Kalra et al. (2005) and Browne et al. (2007). Both these previous studies demonstrated that nearshore wave parameters can be effectively estimated from offshore wave data.

Training of a neural network is performed by presenting the input and output parameters of the training dataset to the network and estimating the weights that connect the neurons. This is iterated over many ‘epochs’ with the weights adjusted each time, until there is convergence. The network is then validated by providing it with a previously unseen set of inputs and comparing the results to the relevant outputs. A typical approach is to use 70% of the data for training and 30% for validation. The output/target data is the set of 2 corresponding visual wave observations at Byron Bay. These visual observations are provided in 4 ranges: 0 – 0.5m; 0.5m – 1.5m; 1.5m to 2.5m; and > 2.5m. There were a total of 710 matched inputs and outputs.

A neural network was designed following the method of Browne et al. (2007) with feed-forward backward propagation of error (Abadi et al. 2015). The input data is wave information from the CAWCR hindcast (Durrant et al. 2014), which has been produced using AUSWAVE/WAVEWATCH III®. The input layer of the neural network had 9 parameters, including significant wave height, two peak wave direction components, peak wave period,
wave energy flux, and information of the primary wave partition (i.e. wave height, mean direction and peak frequency). The output layer consists of 4 parameters where each parameter identifies a single class (i.e. the 4 ranges in visual wave observations). Training against these outputs did not converge to a satisfactory solution and the training yielded an accuracy of about 75% while the testing resulted in an accuracy of about 60%. It should be noted that the size of the training data set in this case (496 samples) is relatively small, and this will limit its performance.

Figure 1 Coastal spectral wave model grid. The left panel shows the extent of the grid domain (solid blue line) as well as the operational wave model grid AUSWAVE-R (solid gray lines). The right panel shows a zoomed in section of the unstructured triangular mesh with variable grid resolution (solid lines). The star indicates the nearshore location and the triangle shows the offshore location referred to in Figure 2.

3. Spectral Modelling

The second approach that we investigated was the implementation of a high resolution coastal wave model (WAVEWATCH III®) for the Byron Bay study area. While more complex data are required for this approach than for neural networks (e.g. high resolution bathymetry data), there are advantages over neural networks. For example, a high resolution wave model can provide more detailed information about the sea-state and does not need to be ‘re-trained’ for any new site.

The spectral wave model covers a small region approximately 50 km by 100 km surrounding Byron Bay (Figure 1, left panel). The nearshore grid (Figure 1, right panel) consists of a variable resolution triangular mesh in which the resolution of the grid increases with the bathymetry gradient and proximity to the coastline. This unstructured grid has 1892 grid points with a resolution of approximately 250 m at the inner boundary and 6 km at the outer boundary (57 active boundary points). The inner boundary is translated 200m from the coastline offshore to avoid the masking of land points in a triangular grid, causing
discontinuities on complex coastlines. During development, active boundary points along the northern, eastern and southern edges of the domain were interpolated from the CAWCR hindcast. Bathymetry data was sourced from the ‘Deepreef’ database with a spatial resolution of 100m (Beaman 2010). Wind forcing was obtained from the U.S. Climate Forecast System Reanalysis (CFS2; Saha et al., 2014) for optimal interpolation along the coastline and consistency with the offshore boundaries.

The high resolution wave model was run over the period November 2012 to April 2016 and compared to the visual observations. Figure 2 shows a comparison for February 2015 between wave heights at the closest point from the CAWCR hindcast (representing current AUSWAVE forecasts), wave heights from the high resolution wave model and the visual observations of wave height. It can be seen that the nearshore wave model is much closer to the visual observations than the offshore model. The visual wave height observations were correctly predicted approximately 60% of the time, showing similar performance to the neural network. It should be noted that the observations are collected manually and by eye and therefore are susceptible to human error of interpretation and large errors. There is considerable scope for further development of the nearshore wave model to improve the wave height forecasts. For example through incorporating a dynamic bottom roughness based on sediment size diameter (Tolman, 1994). Another option is to test different model physics, for example wind input and wave breaking and wave dissipation (Zieger et al. 2015).

Figure 2 Comparison between offshore wave height (black line, depth: 60m), nearshore wave height (blue line, depth: 9m) and visual observations (vertical dashed lines) for February 2015. Please refer to Figure 1 for offshore and nearshore locations.

4. Conclusion

Beach wave height forecasts have been investigated by means of artificial neural networks and a high resolution spectral wave model. While both approaches performed well, due to the paucity of observations, the use of ANN is not feasible at this stage. For the development of ANN, long-term, high quality observations of wave parameters are required at all nearshore locations for which forecasts are required.

Based on these results, a near-real-time forecast system based on a high resolution unstructured
spectral wave model has been set up in research mode to provide nearshore wave forecasts for Byron Bay. It uses boundary conditions from AUSWAVE-R, wind forcing from ACCESS-R and provides 3-day forecasts of nearshore wave height at Byron Bay every 24 hours.

References


AN OPERATIONAL COASTAL SEA LEVEL FORECASTING SYSTEM

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Introduction

The Bureau of Meteorology has recently completed a project that saw the development of new forecast systems of coastal sea-level, with a focus on enhancing the forecasting and warning services that the Bureau provides for coastal impacts resulting from severe weather, such as Tropical Cyclones (TCs).

The project consisted primarily of the development of two new forecast system components:

1. An event-based Tropical Cyclone (TC) ensemble storm surge forecast system implemented for Queensland, the Northern Territory and Western Australia, known informally as the Tropical System.

2. A routinely-run deterministic storm surge forecast system implemented for the entire nation, able to forecast anomalous sea levels due to mid-latitude storms and tropical lows. This system is known informally as the National System.

The output from each of these systems feeds directly into operational forecast tools used within the Bureau, as well as enhancing the Bureau’s capability of providing forecast products for the emergency management sector and other users.

Modelling framework

\textit{Storm surge} is defined as an elevation of water level at the coast resulting from strong winds and reduced atmospheric pressure. Although significant storm surges are very often associated with TCs as they come onshore, they may also be generated in non-tropical areas, most typically by intense low-pressure systems. The definition of storm surge typically includes the effects of \textit{wave setup} – an additional elevation of the water level at the coast due to wave-breaking. This is distinct from \textit{wave run-up}, which relates to the impact of individual waves on shoreline structures or beaches and is often manifest as inundation or ‘over-topping’. \textit{Storm tide} is the combination of storm surge and astronomical tide – if a storm surge arrives at or close to the time of high tide, the impacts can be considerably more damaging than if it arrives at low tide.

The Regional Ocean Modelling System (ROMS; Shchepetkin et al., 2005) was chosen for use in both the Tropical and National Systems, following a review of potential numerical models (Colberg et al., 2013). For this work, ROMS is run in a two-dimensional barotropic mode, using
surface pressure and wind stress to force the ocean free-surface and provide a forecast of storm surge.

Direct calculation of the effects of wave setup, although possible, are currently not feasible in an operational setting. Therefore, the wave setup is calculated using a parametric approach developed by CSIRO (O’Grady et al., 2015) and using the Bureau’s AUSWAVE-R operational forecasts (BNOC, 2016). This approach has minimal computational cost and the necessary inputs are easily extracted from an existing Bureau operational system.

The primary bathymetry data set used to design each system’s model domain is the Geoscience Australia’s 9 arc-second (approximately 250 m) Australian Bathymetry and Topography Grid (Whiteway, 2009). North of 8°S, the GEBCO_2014 30 arc-second grid is used (version 20150318, http://www.gebco.net).

The Tropical Storm Surge System

For the Tropical System, a ‘ribbon grid’ was designed for the model domain. This grid is roughly aligned to the tropical Australian coastline and extends approximately 1000 km offshore. The curved nature of the grid means there is increased resolution at the coast (approximately 1.9 km, compared to 4 km at the offshore boundary). Moreover, there are fewer non-ocean grid points, resulting in increased computational efficiency. A depiction of the Tropical System’s domain is shown in Figure 16.

Prior to the development of the Tropical System, two key TC forecast products existed:

- The Official Forecast Track (OFT), which is produced from a consensus of a number of different models
- A probabilistic forecast of wind speed exceedances, determined from an ensemble of TC tracks spawned from the OFT using the DeMaria method (DeMaria et al., 2009)

The ensemble tracks in the wind speed exceedance product consist of time-series of synthetic vortices and these are used to generate an ensemble of sea-level pressure and surface wind stress to force the Tropical System.

Each ensemble member is used to force the model and the resulting model output of sea-level elevation at coastal model grid points to produce an ensemble of storm surge forecasts. These are combined with a parametric estimate of wave setup and a tidal forecast to produce a probabilistic storm tide forecast. These probabilistic forecasts allow a determination of the likelihood of whether the sea-level will exceed some amount at a given location.
The Tropical System was verified using eight case studies of past TC events, whereby the model was assessed against de-tided tide gauge observations. To facilitate this comparison, rather than run the Tropical System as an ensemble, it was forced using each event’s ‘best track’ data set. These best tracks are analyzed TC track data that are compiled by forecasters for each event at the end of the TC season by incorporating all available data. Using the best track data to force the model, storm surge and wave setup forecasts were added to produce a modelled residual sea-level that can be compared to the observed residuals from tide gauges. An example for TC Yasi (2011) is shown in Figure 17.

The National System uses a simpler grid that is uniformly spaced in longitude and latitude. It has a resolution of approximately 0.02°, which equates to roughly 2 km. A depiction of the domain is shown in Figure 18. This grid design is more efficient and accurate than a ‘ribbon grid’, which is difficult to design optimally due to the concave curvature of the coastline in southern and south-eastern Australia.

The National System is forced using fields of sea level pressure and wind stress taken from the Bureau of Meteorology’s ACCESS-R model (Puri et al., 2013). These fields have a horizontal spatial resolution of 0.11° (approximately 12 km). Wind stress is a function of land surface properties and is typically much larger over land. Therefore, in order to avoid erroneously forcing the model with large land-based wind stress, values at these cells were removed from the ACCESS-R grids and then spatially interpolated from nearby ocean wind-stress values.

The National Storm Surge Forecast System is run four times daily to match the ACCESS-R run schedule. As in the Tropical System, storm surge forecasts from the model are added to the parametric estimates of wave setup and an astronomical tide prediction to produce forecasts of total sea level at the coast.

The National System was evaluated in two ways. Firstly, a 2-year hindcast run was performed to assess the model’s long-term performance and whether the model’s underlying physics can correctly simulate (non-tidal) sea level. 14 tide gauges from the Australian Baseline Sea Level Monitoring Project network were
used to evaluate the hindcast. Overall, there was negligible systematic bias in hindcast sea-level (+3 cm) and a small RMS error (10 cm). The model was generally found to perform better at sites along the southern coast of Australia compared to tropical sites.

Secondly, the model was evaluated for seven case studies of events where anomalously high coastal sea level was observed in different regions of the Australian coastline. These events were attributable to a range of weather systems such as wintertime mid-latitude frontal systems, east coast lows and (ex-TC) tropical depressions. An example is shown in Figure 19, which shows the forecast sea level when a mid-latitude low-pressure system impacted the South Australian coastline in September 2016, producing record observed residual sea-level.

![Figure 19: Time series of modelled surge and wave setup components and their sum (surge+setup) for the September 2016 case study at Thevenard, South Australia. Also shown for comparison is the observed residual sea-level. Times are in UTC.](image)

**Service enhancements from the forecast systems**

Forecast products from both the Tropical System and the National System feed into the forecast and warnings process for storm tide. Some output products are intended as further advice for the internal forecast process, while others are for external users.

From an internal use perspective, both systems enhance forecaster understanding of an event’s possible storm surge related impacts. For example, the ensemble output of the Tropical System is used to generate probabilistic forecasts such as the likelihood of exceeding Highest Astronomical Tide (HAT) at a location over the forecast period. These not only allow forecasters to understood the likelihood of the magnitude and timing of impacts, but also to understand the uncertainties in a given forecast.

For external users, the output can be used to create products that are of a graphical nature. Such products exploit the spatial nature of the system’s output and convey a single or small number of desired key aspects of potential impacts. They may be supplemented by explanatory text or tables that contain more detailed information. However, these products require careful design to ensure not only are users’ needs met, but that any confusion or misinterpretation of the information is avoided.

In this regard, forecast products can take the form existing products that have been well tested and are familiar to users. An example of this is the storm tide warning graphic, also known as ‘totem poles’, which have been used in Queensland for more than a decade. Forecasts from the systems can take this form, or be altered to suit either the system’s capabilities, evolving user needs or other established warning standards.
The process of enhancing storm surge forecast services with these new modelling systems is by no means static. As experience is gained using forecasts from the Tropical and National Systems, forecast products and warnings will continue to evolve. Post-event review of the performance of the systems and the services for which they provide inputs, allows for deficiencies to be identified, understood and addressed. Likewise, users may identify other service needs that will drive future enhancements of the modelling systems.

References


How can GCM and Climate Modellers Assist Hydrologists to Assess Water Security in the 21st Century?

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The basis of this talk is a draft paper prepared by Rory Nathan, Murray Peel and myself, who together have more than 100 years of professional experience in hydrology. In this presentation I address four questions on water security which I define as ‘sufficient water of suitable quality to meet our current and future socio-economic and environmental needs’. The four questions are:

1. What data are required by hydrologists for water security analyses in the 21st century?
2. What GCM assessment measures are available to hydrologists to assess impact of climate change on water security?
3. Do GCM outputs meet hydrologists’ needs for water security analyses?
4. From hydrologists’ perspectives of water security, what scientific challenges confront climate modellers?

In responding to these questions we reviewed more than 250 references of which ⅔ were published during the past 10 years. The science challenges relate to assessing GCMs, aleatory uncertainty and ensembles, epistemic uncertainty, downscaling and importance of convective processes.

My conclusions from our analyses are:

1. GCM modellers should aim to provide realistic time-series estimates of monthly precipitation and temperature while developing more realistic daily values than those provided to date.
2. Assessments of climate change on flood risks are dependent on GCMs being able to simulate sub-daily rainfall. We acknowledge the importance of including both convective and stratiform processes in GCM modelling.
3. GCM modellers should aim to provide a larger number of ensembles (25 would be very helpful) of each scenario run that reflects the aleatory uncertainty associated with stochastic forcing and initial conditions.
4. In reports and papers where GCM outputs are assessed, runoff data (irrespective of whether runoff is a GCM output or from a linked Global Hydrologic Model or Land Surface Model) should be assessed using at least the mean, variance and auto-correlation of annual flows.
USE AND APPLICATION OF CLIMATE AND SEASONAL FORECASTS IN WATER RESOURCE MANAGEMENT

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Introduction

Melbourne Water has provided safe, secure and affordable water services to Melbourne for over 125 years. As part of our core services, we treat and supply drinking and recycled water, remove and treat most of Melbourne’s sewage, oversee major drainage systems and enhance waterways and land for greater community use. In addition to the city’s major water retailers, Melbourne Water also provides bulk water supplies to several regional water authorities. These services cross the whole of the urban water cycle and contribute to Melbourne’s world-famous liveability. Underpinning the delivery of these services is the need to translate weather and climate information to aid the planning, management and operation of these services.

Ongoing developments in climate and seasonal forecasts have resulted in improved information available to water businesses. This paper sets out the context for the use of climate and seasonal forecasts with on water resources management for water supply and highlights some ways water resource managers use climate and other information and discusses potential development needs.

The Melbourne Water Supply system

The characteristics of a water supply system provide the context for forecasting needs. Melbourne’s water supply system is a complex interconnected system of ten storage reservoirs, over forty service reservoirs, 160,000 hectares of catchments and a transfer system comprising hundreds of kilometres of pipelines, tunnels and aqueducts.

Melbourne’s storage reservoirs have a combined storage capacity of 1,810GL. The average volume of water supplied from the system for urban use over the last 5 years was about 413 GL per year. Water sources available to the system include gravity fed supplies from restricted access catchments as well as pumped and fully treated supplies from unprotected catchments.

Streamflow into Melbourne’s water supply is highly variable. The system’s large storage capacity relative to its inflow and water demand means the emptying and filling cycle of the system occurs over many years under average climatic conditions. Despite the large storage capacity, prolonged drought periods in the past have caused significant drawdown of storage, resulting in the need for actions to conserve or replenish supplies. The multi-year drawdown and filling cycle requires a long-term outlook when managing current water resources and planning for future water management needs. The decisions in managing the water resources system include those on the quantity and timing of intake from various water sources, including
desalinated water, distribution of water among various storage reservoirs, bulk water transfers through various paths in the system, discretionary releases to support environmental needs and the timing and capacity of future water needs to meet growing populations in the context of changing of climate conditions.

Ensuring ongoing water security and maintaining an outlook on water supply conditions is a regulated responsibility of water businesses. The key elements supporting water security at any point in time is represented through a combination of climate/weather and streamflow conditions, water in storage and expected commitments, consumptive, environmental and other water demands, availability and use of non-traditional water and system operational strategies.

Melbourne Water holds only the water entitlements to harvest water on behalf of primary water entitlement holders (metropolitan and regional water businesses). As a result a key element of our activities in providing for water security for all entitlement holders for the short and long term is to provide water related information to primary entitlement holders to enable them to efficiently there available share of the total water available to Melbourne.

The Framework for Adaptive Water Management

As regulated water businesses, the metropolitan water businesses have developed a framework for managing short-term climate variability and longer term climate change with various planning and management processes to support these (see Figure 1). Climate and forecast information is used within these different time frames, for example:

- **Daily** – use of 1 to 7-day weather forecast to support information on expected water demand and streamflow for managing operations and releases for water supply and environmental flows.
- **Monthly to Seasonal** – use of seasonal climate and streamflow forecasts and translate to water management information to primary entitlement holders, including seasonal water determinations and storage outlooks for up to 12 months
- **Annual** – Seasonal climate and streamflow outlooks and long term water resources modelling supports the annual Water Outlook and desalinated water order advice (published on our website), annual operating plan and environmental watering plan.
- **Multi-decadal climate change.** Melbourne Water and the retail water businesses use climate change projections to support key planning documents such as the recently released Melbourne Water system strategy (Melbourne Water, 2017)

To prepare for and support actions during drought periods, an adaptive framework based on storage zones, representing volumes of water in storage is used and reported on in the annual water outlook. These zones have been determined based on expected water demand, and water availability during a ‘design drought’. For this purpose five-year duration low probability events, based on climate change scenarios, are derived and used to calculate the volume which drought response actions are required to provide for ongoing security (Tan and Rhodes, 2013).

These methods, and the monitoring of expected storage volumes are supported to some extent by available climate and streamflow forecast information, but requires further interpretation by water businesses to apply within business planning. For example, the Bureau of Meteorology seasonal streamflow forecasts are provided at key locations for a 3-month outlook. In terms of
the Melbourne Water supply system, with the extensive carryover storage 3-month forecasts have limited utility when many of the major decisions are made on an annual basis. As a result Melbourne Water has developed a method to produce a sample set of 12-month streamflow scenarios based on the prior information provided by the Bureau’s 3-month streamflow forecast and ENSO outlook which is then used as inputs into Melbourne’s water system model. This highlights how Melbourne Water utilised the limited streamflow forecast and climate outlook information by translating them into 12-month storage outlook to guide water management.

Where knowledge gaps exist, Melbourne Water will often engage with researchers to build knowledge to support business decisions. As an example of recent research support we were a funding partner and steering committee member of the University of Melbourne South East Australia Recent Climate History (SEARCH) (Climatehistory.com.au, 2017) program which was the recipient of the 2014 Australian Museum Eureka prize for excellence in interdisciplinary scientific research. This information improved our understanding of the historical context of the millennium drought. Melbourne Water is also currently a key funding partner in the Victorian Drought Risk Inference Project (VicDRIP) (Unimelb.edu.au, 2017). The study will extend palaeo-climate data developed in the SEARCH program to investigate the history and future risk of decadal to multi decadal droughts (mega droughts) under climate change, which will inform water management.

### Challenges in water resource management

#### What are the gaps – improved understanding and forecasting

Climate and weather forecasts are only one element of the uncertain environment in which water businesses operate. Uncertainties in population growth and water demand, alternative water sources, economic impacts on non-residential use, variability in environmental needs, and the development in water grid and market are all elements in assessing future water supply and demand balance.

Nevertheless there are a number of opportunities to improve information. Some key areas may include:

- Understanding and communicating drivers and linkages in climate.
- Understanding causes and modelling of changes in catchment runoff responses
- Enhancing and extending streamflow forecasting beyond 3 months out to 12 months
- Developing methods and tools to facilitate direct application of Bureau’s short-term and seasonal climate prediction outputs to drive water businesses’ hydrological models
- Multi-year/decadal information. Improved understanding of the long-term variability in the context of changing climate would provide significant benefits for water management and investment planning given Melbourne’s multi-year carryover storages, We understand CSIRO Climate Science Centre (CSIRO, 2017) is leading a new initiative in decadal forecasting for Australia.

### Linking research to application

In focusing on research opportunities, technology transfer and building capability can be overlooked. Climate science, like hydrology, water resources management are specialist skill
sets, required many years of developed specialist knowledge. The increasing specialisation and complexity of assessments and decision processes, and the desire for instant information, means limited expertise can be available to transition directly from climate science and forecasting information into water management practice.

In recent years consideration has been given to the role of the knowledge broker (Verdon-Kidd et al., 2013) and the role that these people play in linking climate information to water resources decision processes. However other groups, such as the Water Utility Climate Alliance (WUCA) (Wucaonline.org, 2017) in the United States, seeks to develop a smart community of water users through building capability in water professionals to better understand climate change information to aid climate adaptation processes. WUCA has recently conducted training which gave water management practitioners a better understanding of issues around climate change science, uncertainty in the climate projections, downscaling, decision making processes and limitations, and the communication of this information.

The Victorian Government has recently released guidance documents on the use of climate change projections for water supply planning (DELWP, 2016). These were prepared with significant input from climate researchers and in consultation with water businesses to understand user needs. This has resulted in high quality information and practical guidance including planning scenarios and projections enabling direct application into water resources models consistently across the state.

**Future directions – user needs consultation and research partnership**

This paper highlights some opportunities in understanding and forecasting of weather, climate and for the research and scientific community to engage more closely with the practitioners in the water businesses to understand the problems faced by water managers and decision makers, the types and gaps of information needed by the users, increased research partnership, and methods to present and communicate research outputs for direct applications by water businesses to improve water planning and management.

**References**


WATER FORECASTS IN AUSTRALIA AT SEASONAL TIME SCALE – RESEARCH ADVANCES AND CHALLENGES

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Each month, the Australian Bureau of Meteorology issues operational seasonal streamflow forecasts of total water volumes for three months ahead for over 350 locations across Australia (http://www.bom.gov.au/water/ssf/). The forecasts are created using modelling approaches developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and other partners. Forecasts of seasonal streamflow can inform tactical management of water resources, allowing water users and managers to plan operational water management decisions and assess the risks of alternative water use and management strategies.

Forecasting streamflow over the next month, season and multiple seasons is a challenging task, because the predictability of climate over these forecast horizons is low. On the other hand, initial conditions of soil moisture, groundwater and other water stores in a catchment can have some relatively predictable effects on streamflow months ahead. State-of-the-art forecasting methods aim to (1) quantitatively capture, as much as possible, both sources of streamflow predictability and (2) statistically represent the remaining predictive uncertainty in a reliable manner.

In this presentation, we will give an overview of scientific approaches for seasonal streamflow forecasting, and research progress made in Australia in improving the skill and statistical reliability of ensemble forecasts. We will discuss the key challenges in further improving water forecasts and integration with water management applications. We will outline future directions for research and services.
LESSONS LEARNED FROM THE OPERATIONALISATION OF SEASONAL STREAMFLOW FORECASTS OVER THE DECADE

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The Bureau of Meteorology (the Bureau) has been delivering seasonal streamflow forecasts (SSF) to the public since 2010 (Tuteja, 2015; Figure 1). Every month, the service provides ensemble forecasts of streamflow volumes for the next three months at gauged sites or inflows to major water storages across Australia. Starting with 21 locations in the south-eastern mainland, the service has expanded to 181 locations across Australia, with additional 137 locations ready for public release and available to registered users.

The current SSF forecasts are generated from a Bayesian Joint Probability statistical model (Robertson and Wang, 2012). In addition, forecasts from a dynamic modelling approach running a rainfall-runoff model forced with seasonal rainfall forecasts is under development (Lerat et al., 2014). We are planning to use rainfall forecasts from ACCESS-S, the next generation global climate model of the Bureau, and release individual monthly time series of streamflow forecasts in 2018.

In developing and expanding the SSF service over the last decade, the Bureau’s Water Forecasting Services (WFS) section faced and overcame considerable challenges and learned many valuable lessons along the way. We present five such lessons which are important for successful development and operation of the SSF service. Illustrative cases and examples are also provided.

The dynamic modelling approach we are developing uses rainfall forecasts from a climate model as input to a hydrological model. Ideally, the climate model must capture the large-scale dynamics in climate drivers influencing seasonal rainfall variation to reliably indicate the likely trend in rainfall. The climate model should also generate accurate rainfall forecast time-series at the catchment scale.

Our examination of rainfall forecast quality from ACCESS-S has revealed that for many catchments, rainfall forecast errors are still the dominant source for uncertainty in streamflow forecasts, dwarfing errors arising from hydrological modelling. To overcome this barrier, we have worked cooperatively with our research partners to identify an appropriate method that can generate unbiased and reliable rainfall forecasts applicable at the catchment scale.

Collaboration with CSIRO and several universities over the past decade has laid the foundation for the current SSF service. Through this experience, we have learned that full transition from research to operation is not always achievable. Operational forecasters should be ready to test new ideas and allow researchers to explore new territories. On the other hand, researchers need
to understand some of their deliverables might not be adopted due to constraints in an operational environment.

For instance, the University of Adelaide team proposed several Bayesian calibration methods for the dynamic modelling approach. However, we found only one of the proposed methods was appropriate for the SSF service because the other methods were too complex to apply at a national scale (Tuteja et al., 2011). Another deliverable from CSIRO comprising of a method for long-range (6-12 month) streamflow forecasts was revised in response to our request to have a more parsimonious model structure (Bennett et al., 2016). Several other research products that have demonstrated promising results are waiting for additional funding to be operationalised.

Highly variable hydroclimatic conditions across Australia pose unique challenges when developing modelling methods and systems applicable at the national scale. For example, when we expanded the SSF coverage from the south-eastern mainland to the entire nation, we identified limitations in the operational modelling methods, particularly when forecasting streamflow volumes in ephemeral and intermittent streams. This required further development in modelling methods to ensure they were applicable across the nation.

As the SSF service continues its development as a nation-wide service, any change to the service requires close scrutiny. To facilitate this assessment, we have built a streamlined system of forecast verification, which allows testing of proposed changes on all service sites and automatically detects abnormal characteristics in forecasts. Comprehensive model evaluation at the national scale must be considered as a core activity of the service team so as to avoid mistakes associated with hasty adoption.

Designing forecast products and websites was a long journey, involving numerous interactions among scientists, developers, designers, users and key industry stakeholders. Along the journey, we found that rapid prototyping was one key factor that has contributed to successful development of SSF.

When designing new forecast products or websites, we adopted an iterative process to prototype, review and refine quickly. Starting from rough paper sketches, we mocked up new graphs or user interface and requested feedback from diverse users and stakeholders. We then refined details of the prototypes and re-submitted them for further review. Through this iterative process, new forecast products and web portal therein gradually took shape, reflecting the input of our end-users as well the SSF service team.

Forecast information is intended to be used to inform decisions and improve social, economic and environmental prosperity. The Bureau’s responsibility is to ensure the service produces seasonal forecast information that is clear, appropriate for its audience and suitable for use in decision making.

It has taken considerable time and effort to develop meaningful relationships and engagement with our stakeholders. Only recently, some years after the service commenced, we are seeing active movement to adopt the streamflow forecasts for water supply operations. To build up more momentum in user adoption, we are developing several case studies with leading industrial partners to share their stories of SSF adoption with other agencies.
Figure 20 The seasonal streamflow forecast website of the Bureau of Meteorology at http://www.bom.gov.au/water/ssf/

References


URBAN FLOODING INCREASING, WHILE THE COUNTRYSIDE DRIES UP – A GLOBAL ASSESSMENT OF WATER SECURITY WITH RISING TEMPERATURES

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Rising temperatures have been shown to result in increases in short-duration rainfall extremes across the world. Additionally, it has been shown (doi:10.1038/ngeo2456) that storms will intensify, causing derived flood peaks to rise more. This leads us to speculate that flood peaks will increase as a result, complying with the storyline presented in past IPCC reports. This talk, however, shows that changes in flood extremes is much more complex than thought earlier. Using global data on extreme flow events, the study conclusively shows that while the very extreme floods may be rising as a result of storm intensification, the more frequent flood events are decreasing in magnitude (doi:10.1038/s41598-017-08481-1). The study argues that changes in the magnitude of floods are a function of changes in storm patterns and as well as pre-storm or antecedent conditions. It goes on to show that while changes in storms dominate for the most extreme events and over smaller, more urbanised catchments, changes in pre-storm conditions are the driving factor in modulating flood peaks in large rural catchments. The study concludes by providing recommendations on how future flood design should proceed, arguing that current practices (or using a design storm to estimate floods) is flawed and needs changing.
PRESERVING CULTURAL HERITAGE IN THE FACE OF ANTHROPOGENIC CLIMATE CHANGE

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Communicating the vulnerability of cultural heritage sites to the impacts of climate change has been recognized as an important planning option in climate change adaptation. Mass global access to digital media offers the potential for highly effective sharing of information, experiences and research outcomes relating to cultural site adaptation. Production of a video documentary titled Places in Peril: Archaeology in the Anthropocene aimed to undertake such communication. The resulting video fills a gap in the filmic medium: no archaeological documentary film-making focusses on cultural site preservation in the face of anthropogenic climate change; and within the emergent sub-genre of film addressing climate change, none focusses on managing the impacts on cultural heritage sites. Production of the documentary addressed the question of how to effectively frame and convey to an international audience the significance climate change poses to cultural heritage sites so as to generate support for adaptive programmes and further research partnerships and resources. In so doing it sought to feature analysis of the issue by the custodians of cultural sites, and allow them to elucidate the types currently and potentially impacted, plus the nature of those impacts, within the context of scientific research they are undertaking to address the issue. In presenting their analyses, participants were given the opportunity to convey the social and cultural significance of their heritage sites and why they are worthy of conservation. Places in Peril investigates the proposition that the issue of climate change and cultural sites is readily and effectively communicable via the digital moving image.
PROGRESS TOWARDS AN OPERATIONAL EVENT ATTRIBUTION SYSTEM FOR AUSTRALIA

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In Australia we experience many extreme weather events. Whether it’s heatwaves, intense rainfall, or droughts, these types of extreme weather have large societal, economic and environmental impacts. For these reasons it is important to understand how and why human-caused climate change and natural climate variability influence extreme weather events.

This is where the field of event attribution proves useful. By using climate model simulations and differentiating the roles of climate change and variability for specific event types we can improve understanding of Australia’s changing climate extremes. Event attribution also allows for clearer communication of climate change risks to stakeholders and the public in the context of recent events.

There is a large body of peer-reviewed work in Australia on the attribution, primarily to anthropogenic climate change, of recent climate extremes. Using this work as a platform I am developing an operational event attribution system. Through applying peer-reviewed methods and thorough model evaluation, rapid attribution statements can be made for recent extreme events. I will present early development of this project.
CLIMATE PROJECTIONS PRODUCTS AND SERVICES: PROVIDING VALUE AT THE MULTI-DECADAL SCALE

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Introduction

Climate change due to human influence is affecting all sectors and communities in Australia, and climate change and associated impacts are set to continue in coming decades. Understanding what impacts climate change may bring, and how to adapt to them, is an increasingly urgent priority. Climate projections are designed to provide plausible scenarios of future climate to inform climate change planning, and also to motivate emissions reductions. There are various challenges in generating and communicating climate projections, and maximising their usefulness.

Climate change projections look ahead to periods such as 2050 and 2100, and this timescale has some key differences from the weather and climate variability timescales. Prediction of the first kind (the evolution of the climate system given the initial state) is severely limited at this timescale, so projections mainly rely on predictability of the second type (the change to statistical properties of the system in response to external forcings, essentially a boundary value problem). Also, beyond the next few decades, changes to the climate become increasingly dependent on the external factors (primarily greenhouse gas concentrations), which are not predictable. Additionally, we don’t have a perfect understanding of how the earth system responds to forcing scenarios beyond those previously observed, and the models used are imperfect and contain systematic biases. Therefore, projections aim to provide plausible ranges of change to the climate state under credible scenarios of emissions. Such projections must be appropriately used within the limitations and uncertainty inherent in the nature of this timescale.

Unlike weather forecasts, climate projections can’t be used in a ‘predict then act’ framework and in fact can’t be used in a probabilistic sense. Instead, projections can be used as scenario-generators, where plausible future climate scenarios can inform and stress-test adaptation options, but not rigidly dictate actions and responses.

Tools and methods to add value

Ensembles of global climate models and high-resolution downscaling models are key tools for generating climate projections. However, raw model output is not useful as it is. Outputs from models need to be critically assessed, screened, processed and transformed into information products and services that are useful for various analyses and sectors. Projections have four key markers of success:

- Scientifically credible: not strictly ‘accuracy’ given the nature of the endeavour, but projections need as much scientific robustness as possible
Salient: relevant to impacts and adaptation research and decision-makers
Legitimate: the perception that the information is respectful of stakeholders’ divergent values and beliefs, unbiased and fair
Actionable: projections are able to be used in decisions

The national climate projections set of products and website from CSIRO and the Bureau of Meteorology (www.climatechangeinaustralia.gov.au) uses the full suite of climate observations, cutting edge science and research as well as the latest ensemble of global climate model simulations and high-resolution downscaling in various communication products on climate change in Australia. These products are combined with various services such as training courses, presentations, briefings, webinars, data requests and expert advice to enhance the appropriate uptake and use of the projections information.

The national projections cover the atmospheric and marine domains, including such areas as averages of rainfall and temperature, atmospheric extremes including storms, evaporation and water balance, snow, fire weather, sea level rise, coastal storms and extreme sea level, sea surface temperature, sea surface salinity and ocean acidification.

The projections products and website have several key focus areas, including:

- Background learning and guidance material
- Reports, summaries and brochures
- Simple web tools to explore the projections data by region and by variable (atmospheric and marine)
- Datasets – tables, ranges of change, spatial data and time series
- Intermediate and advanced web tools that provide sophisticated services, such as: thresholds explorer for looking at days over/under various climate thresholds in future scenarios, a tool to help envisage what a climate change looks like by providing geographic analogues, and a tool to select representative model outputs for using in impacts research
- Links to further information and for taking climate projections to impacts and adaptation analysis

In this talk I will describe the issues involved in producing climate projections before describing how the products and services of the Australian national projections add value for the users of projections.
WHAT WILL FUTURE CLIMATE CHANGE SERVICES LOOK LIKE?

Karl Braganza

_Bureau of Meteorology_

Climate services around the globe continue to evolve at a very rapid rate, mostly in response to the need to inform current climate change adaption, and the need to better define future risks.

Traditional services such as real-time and historic climate monitoring, and seasonal climate prediction, will increasingly include a consideration of user requirements for dealing with these risks, such as through a seamless alignment with climate projections and future extreme scenarios. Such projections will move far beyond median estimates of average future change, to fulfil a demand for worst-case scenarios for exploring risk, and for stress testing management systems and physical assets.

This change reflects a change in requirements and demand from stakeholders of climate information. Examples can be found in all sectors of the economy and environmental management. For example, emergency managers in the area of natural hazards, public safety and disaster risk reduction are increasingly wishing to understand how risks and vulnerabilities have changed, and what provisions need to be made for the medium-term future. Similarly, natural resource and built asset managers need clearer information on the likely range of extreme impacts on the environment and critical infrastructure.

The largest anticipated change in demand may occur in the finance sector of the global economy, which is undergoing significant regulatory shifts as an outcome of the Paris agreement. Most significantly, firms and corporations will include a disclosure of climate related risks as part of their fiduciary duties.

These changes suggest a large increase in the need for granular data for describing future physical risks from climate change, and accompanying knowledge and information services.
The Centre for Australian Weather and Climate Research is a partnership between CSIRO and the Bureau of Meteorology.