IMPACT-BASED FORECASTING FOR THE COASTAL ZONE: EAST COAST LOWS

Final project report

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Cover: Picture illustrating wind & rain hazards. Source: Harald Richter

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The project is grateful to Anthony Day and Simon Gethin from the NSW SES for the provision of the BEACON damage assessment data for the 20-22 April 2015 East Coast Low event, and to John Moore from FRNSW for the provision of the EICU dataset for the same event.

EXECUTIVE SUMMARY

The Bushfire and Natural Hazards CRC project *Impact-based forecasting for the coastal zone: East-Coast Lows* set out in 2017 to demonstrate a pilot capability to deliver wind and rain impact forecasts for residential housing from an ensemble of weather prediction models runs. The project was a collaborative effort between the Australian Bureau of Meteorology (Bureau) and Geoscience Australia (GA).

The project was initially focused on the wind and rainfall impact from the 20-22 April 2015 east coast low event in New South Wales (Wehner and Maqsood 2015). The wind and rainfall hazard data were provided by a 24-member ensemble of the Australian Community Climate Earth System Simulator (ACCESS; Bureau of Meteorology 2018) model on a 1.3 km grid, with damage data provided by NSW State Emergency Services (SES) and the Emergency Information Coordination Unit (EICU. Exposure data were sourced from the National EXposure Information System (NEXIS; Nadimpalli et al. 2007; Power et al. 2017) at GA. Heuristic wind vulnerability functions, derived in a previous project, were also provided by GA, while no large-scale rain vulnerability relationships existed.

Through the utilisation of GA's *HazImp* software, we developed and tested a workflow that integrated the numerical weather forecasts, vulnerability relationships and exposure data at the community level, and early in the second year of the project we started producing the first spatial quantitative wind impact plots.

The multi-hazard nature of the east coast low event, the relatively low wind speeds relative to the design wind speeds for the affected residential buildings and the available damage assessment data made attributing the observed building damage to a single hazard such as wind or rain difficult. Wind damage to residential housing in this case was largely due to tree fall, as opposed to structural failure, while the most severe damage for the Dungog event was due to flood inundation. To increase the utility of the damage assessment data we recommended early in our project that the SES/EICU damage survey templates should record multiple damage states and linkages between damage and the associate hazard(s). Such expanded recording practices would lead to improvements in the development of the hazard-damage relationships, a requirement for progress in quantitative hazard impact modelling. Additional uncertainty arose through the NEXIS exposure data which are statistically inferred at the Dungog township and are therefore merely indicative of the actual building attributes.

During the second year of the project a range of scope reductions were introduced in response to our previous and emerging findings during this second year.

- The uncertainty in the exposure and vulnerability information and arising difficulties in verifying the quantitative wind impact forecasts against compatible damage assessment data precluded us from a more detailed exploration of the wind forecast uncertainties afforded by the 24-member ACCESS ensemble. The project switched to source its wind information mainly from the 1.5 km BARRA-SY reanalysis as the most accurate high resolution wind data source available.

- Attempts to derive rain damage vulnerability relations were stifled by extreme sensitivity of our results to any variation in the rain inputs. A decision was made to focus solely on the better defined wind impacts.
- We attempted to apply the wind impact prediction system to a number of other wind damage events such as the December 2015 Kurnell tornado event near Sydney. The number of viable cases was low to begin with, as these required the co-availability of high resolution reanalysis wind data (limited spatial domains within Australia) and high quality damage assessment data (limited to more recent years). However, all of the available cases that satisfied the reanalysis and damage data restrictions still suffered from limited wind predictability given that the highest wind speeds in these events were driven by small-scale meteorological processes that cannot be predicted accurately in space and time.

The project set up the end-to-end workflow from wind hazard to spatial impact. These spatial impact outputs were delivered into the Visual Weather system at the Bureau of Meteorology, foreshadowing the possibility of easily achievable future visualisation to operational meteorologists.

To evaluate the performance of the quantitative wind impact forecast that we had produced, very careful and detailed processing of the available damage data was needed to remove damage reports due to tree fall, as opposed to structural failure, rain ingress, and flood inundation. We have now shown that the inclusion of exposure and vulnerability information can outperform a wind impact forecast that only uses a plain wind hazard prediction. In other words, the Dungog case study suggests that the extra effort needed for the quantitative inclusion of exposure and vulnerability information is a promising approach in the pursuit of future quantitative impact forecasts in Australia.

To gain a better understanding of how other agencies have approached the wind impact prediction problem, we also conducted an extensive literature search which resulted in a selective summary of meteorological hazard impact prediction systems. These findings have been submitted to the Australian Journal of Emergency Management as a review paper.

We finally applied our impact forecast methodology to a second extreme weather case during May 2020 in Perth. An extra-tropical cyclone produced widespread wind damage with wind gusts in excess of 100 km/h recorded over many hours. In this case we found that wind impact forecasts are sensitive to the fluctuations in wind gust forecasts produced by the Bureau's high-resolution real-time weather prediction models. Alongside the multi-hazard nature of damage to residential buildings, this impact sensitivity to the hazard constitutes a second complication for the quantitative prediction of wind impacts.

END-USER PROJECT IMPACT STATEMENT

Simon Louis, *NSW Regional Office, Bureau of Meteorology*

A core pillar of the mission of the Bureau of Meteorology and our partners in emergency services is to reduce the loss of life and damage to property in extreme weather events. Critical to this mission is the ability to provide forecasts and warnings of weather conditions in a way that facilitates effective decision making by officials and members of the public. These decisions can range from the type of language used in public messaging, to pre-positioning of emergency response teams, to tactical decisions made by on-the-ground responders. Fundamental to this decision-making process is the ability to match up intelligence about likely weather conditions with knowledge about risks and vulnerabilities in the community.

The work of the Impact Based Forecasting BNHCRC project team is a critical first step in bridging this gap between hazards associated with weather conditions and the vulnerability of the community to the hazards. By establishing a proof of concept approach to combining these two pieces of the puzzle to produce explicit forecasts of impacts from extreme weather events, this work will lay the ground work for potential future operational impact based forecasting systems. A key challenge in designing a system of this type lies in gathering disparate sources of data and making sure that existing procedures for collecting impact data are fit for purpose. An important output from the project may include recommendations on how impact data are collected in future.

It is likely that explicit impact forecasting systems will become a key part of the tool kit for operational meteorologists and emergency services in the future. I look forward to the continued work of the BNHCRC team exploring the possibilities in this area.

PRODUCT USER TESTIMONIALS

Roger Mentha, *Fire and Rescue NSW*

The project has brought significant research to end-users at both the AFAC conference in Melbourne and the Research Advisory Forum in Perth. These two engagements provided opportunity for direct feedback from end-users and the opportunity to bring the scientific experts and emergency service end-users together. Presentation of options for utilisations and feedback from end-users on applying the research to protecting critical infrastructure was beneficial and will assist year 3 outcomes.

INTRODUCTION

Strong surface wind gusts and heavy rain are meteorological hazards that are predominantly produced by storms such as extratropical cyclones (including east coast lows), tropical cyclones or thunderstorms. Interest in these hazards from a response agency point of view lies in their impact on the natural and built environment. At present, weather forecast models still predict mostly 'raw' meteorological output such as surface wind speeds at certain times, or rain accumulations over a specified period. This model output needs to be combined with exposure and vulnerability information to translate the forecast hazard into predicted impact.

Weather Services around the world have gradually been shifting their focus from the delivery of weather and hazard information to value-added information that better characterises the impacts that such hazards can have. Weather impact forecasts have matured or are maturing to the point of operational delivery. One such example is the impact and likelihood matrix employed by the Met Office Severe Weather Warning Service in the UK (Neal et al. 2014).

The prediction of weather impacts can be accomplished on many levels of sophistication. A simple approach to estimate impacts is to recast weather variables produced by a numerical weather prediction model in terms of how unusual a specific forecast is relative to a reference climatology (Perry 2017). The implication is that the more unusual an event the more likely it is that the event has an appreciable impact as community preparedness should scale with the degree of departure from normal conditions. The other end of the spectrum is marked by impact prediction models where the effect of a hazard (or interacting hazards) is quantified in full. Examples of impact models are the Vehicle Overturning Model (Hemingway and Gunawan 2018) or the Surface Water Flooding Model (Aldridge et al. 2016). These hazard impact models are operational or close to operational at the UK Met Office. In-between these two types of impact estimation approaches are various levels of hazard, exposure and vulnerability specifications that, to a varying extent, invite the user to subjectively integrate the various impact drivers (hazards, exposure, vulnerability) in an attempt to estimate the resulting impact.

As part of the three-year Bushfire and Natural Hazards CRC Project "*Impact forecasting in the coastal zone: East coast lows*", we integrated wind hazard hindcasts and forecasts with information on vulnerability and exposure to estimate the wind impact on residential properties. The study aimed to produce a proof-of-concept system to demonstrate that high-resolution weather forecast models, exposure data and vulnerability relationship estimates have reached a stage of maturity that allows for the production of meaningful spatial wind impact estimates for residential buildings.

The specific aim of this project was to develop a pilot capability to produce useful spatial impact predictions for residential housing due to extreme wind in Australia's coastal regions. Such predictions are expected to improve timely mitigating actions by a wide range of stakeholders, in particular the emergency response agencies. This pilot project focused on the 20-22 April 2015 Dungog east coast low event as this type of extratropical cyclone often severely impacts the subtropical east coast of Australia. More widely, these events produce a range of hazards that are relevant to the coastal zone, i.e. high wind, rain, flooding and coastal surge and erosion. An east coast low, rather than a tropical cyclone event, was chosen, in part because the larger size of east coast lows allows for more reliable wind field predictions by numerical weather prediction models as utilised in this work. The focus of this project was on the wind and rain hazards, which was based on user feedback together with the feasibility of combining relevant hazard forecasts and impact models. Floods are of interest but were not included in this project because Bureau flood warnings are already addressing some of the flood impacts which in turn are translated into more local impacts by individual local councils. More specifically, the project goals included:

- determination of the type of impact information based on the wind/rain hazard that would be most valuable to end-users
- development and testing of an approach to integrate numerical weather forecasts, vulnerability relationships and exposure data at the community level
- development of spatially and temporally varying and meaningful impact information
- testing of the project approach for a small number of previous events
- determination of how data resolution, availability, etc., constrain the impact information that could be provided in a future operational system
- development of a pilot impact-based forecasting system.

DATA & METHODS

The project originally aimed to demonstrate that standard surface wind and rainfall output fields from a high-resolution (or "convection-allowing") numerical weather prediction (NWP) model ensemble can be processed to provide a useful spatial estimate of wind and rain impact on residential buildings up to two days in advance. This goal was reduced in scope to focus on the demonstration of a useful spatial wind impact estimate for residential buildings given wind hazard prediction from the deterministic Bureau's ACCESS-City model (or its attendant reanalysis product such as BARRA-SY, Su et al. 2019 and Su et al. 2021).

This processing chain or *workflow* requires three fundamental input fields: hazard, exposure and vulnerability information. A hazard in the project context can be described as the wind field of a magnitude that is closely related to the essential causal mechanisms for an impact (in this case damage to a residential building). Exposure information describes what assets are acted upon by the hazard or hazards, and vulnerability describes how susceptible an asset is to the actions of a given hazard. This section describes what data the project sources for its hazard, exposure and vulnerability estimates, and how these data are processed to arrive at spatial impact estimates.

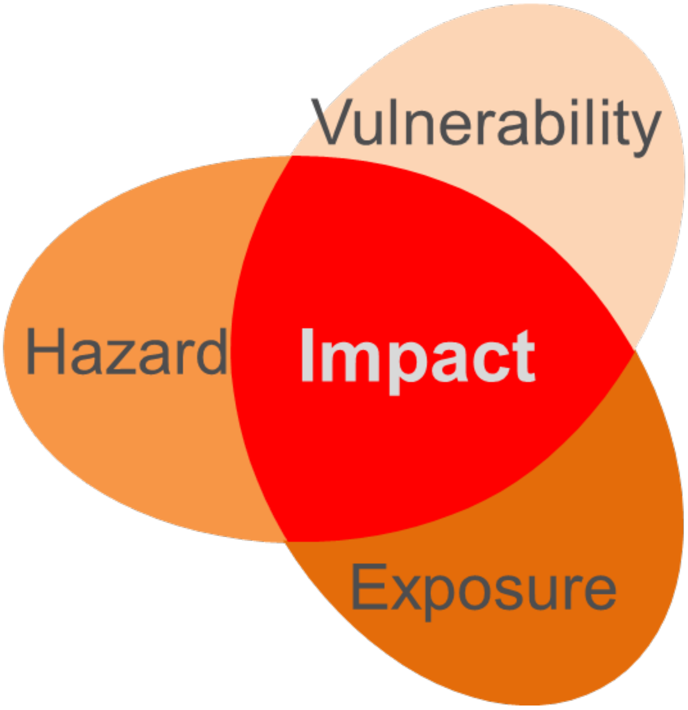


FIGURE 1: INTEGRATION OF THE THREE COMPONENTS - HAZARD, EXPOSURE AND VULNERABILITY - TO ARRIVE AT AN ESTIMATE OF IMPACT

HAZARD DATA

The hazard data used in this project is derived from the output of the "City Model" of the Australian Community Climate Earth System Simulator Australian Parallel Suite 3 (ACCESS-C3; Bureau of Meteorology 2018). Each cycle, the operational ACCESS-C3 model produces hourly wind outputs on a 1.5 km horizontal grid out to about two days in advance. The model runs four cycles per day. We also utilised near-surface wind estimates from the BARRA-SY reanalysis (Su et al. 2019, 2021) which is also available on a 1.5 km grid. Both, the ACCESS-C3 model and the high-resolution reanalysis essentially based on the same model, are state-of-the-art weather prediction / analysis systems that have been tested extensively at the UK Met Office and at the Australian Bureau of Meteorology. The ACCESS global model (a coarser resolution version of ACCESS-CE3) ranks among the top three numerical weather prediction models in the world, and is therefore one of the best tools for the provision of a reliable and high-quality surface wind field.

The raw model output does not deliver the "best" actual hazard estimate straight away, but some processing is required first. For example, the basic model wind output, such as the mean wind at 10-m above ground level ($U_{10m;}$ Fig. 2b), is not the most suitable estimator for wind damage, given wind damage is more closely related to wind gusts rather than ~20 minute mean winds. It is therefore useful to distinguish between raw model output and a related wind hazard specification. A promising model output variable for estimating wind damage is the ACCESS-C3 wind gust diagnostic, U_g, derived from the 10-m above ground mean wind speed, but also factoring in the effects of turbulence such as planetary boundary layer eddies (Fig. 2d). U_g is calibrated to represent a 3 second gust wind speed (P. Clarke, pers. comm.), and corresponds closely to the observed gust wind speed recorded at automatic weather stations. We note that there is still a residual wind gust time averaging discrepancy between the model output and the heuristic vulnerability functions (below) which assume an 0.2 sec wind gust.

Apart from the 10-m gust diagnostic U_g and the less suitable 10-m mean wind, other options exist to sensibly define a wind-based damage proxy or hazard. In this project we utilised the 900 hPa ("gradient level", approximately 1-km above sea level) winds on the assumption that turbulent mixing can transport such winds to the surface under the right meteorological conditions (Fig. 2a). We also used a neighbourhood maximum gust wind hazard estimator where every grid box is set to the maximum wind gust within a 40-km radius (Fig. 2c). Such neighbourhood maximum concepts are widely used in severe convective forecasting using convection-allowing models (Roberts et al. 2019; Kain et al. 2010) and take into account spatial uncertainty of where the maximum gusts may occur.

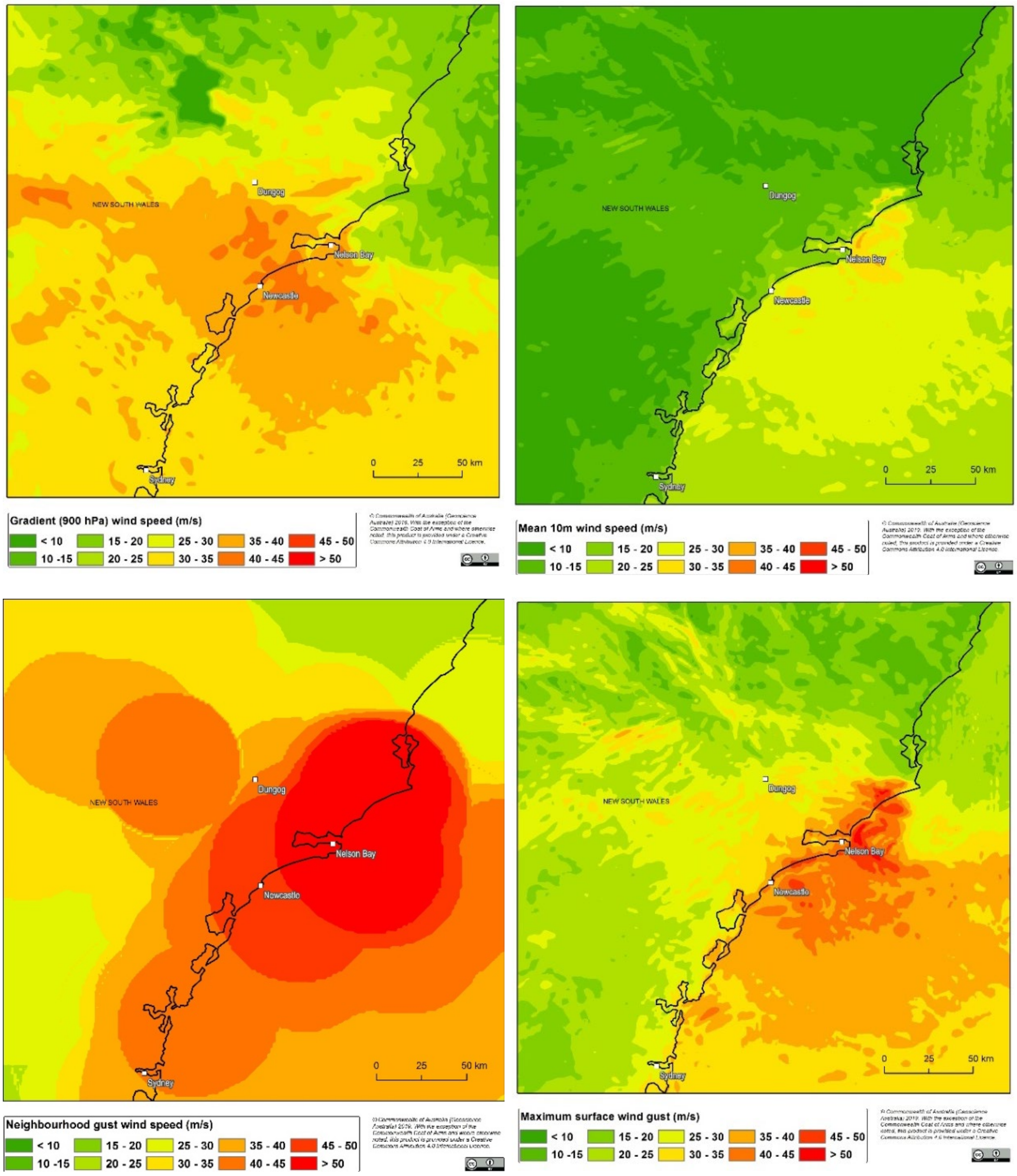


FIGURE 2: FOUR CHARACTERISATIONS OF WIND HAZARD FOR THE 2015 EAST COAST LOW EVENT, AS SIMULATED IN THE BARRA-SY REANALYSIS (CLOCKWISE FROM TOP LEFT): POINT GRADIENT WIND SPEED, POINT MEAN WIND SPEED, POINT GUST WIND SPEED AND NEIGHBOURHOOD GUST WIND SP SPEED. ALL VALUES ARE IN UNITS OF METRES PER SECOND.

The four variants of near-surface wind fields depicted in Fig. 2 allow us to ascertain how uncertainties in the wind input fields will carry through into variability in the quantitative wind impact predictions shown later. As a proxy useful for the prediction of rain ingress, model rainfall accumulations over varying time periods (10 minutes, 30 minutes; 1 hour; 3 hours; 6 hours, 12 hours and event maxima) are used as the rain hazard fields.

The project initially considered the inclusion of fine-scale topography, shielding and terrain roughness information beyond the information available through the ACCESS-City model, but abandoned that approach based the lack of reliable national datasets that would be required for the pursuit of a national capability in wind impact modelling.

VULNERABILITY DATA

Vulnerability is a term used to describe the relationship between severity of impact on an asset from a hazard of given magnitude. It can be quantified and expressed through vulnerability of fragility functions. Vulnerability functions relate average damage suffered by a population of similar assets to hazard magnitude. Fragility functions relate proportions of a population of similar assets in different damage states to hazard magnitude. Often, both types of functions are presented as S-shaped curves although there is no requirement to do so. This is particularly the case for flood hazard where the required repair increases in a series of steps as water depth increases.

Vulnerability and fragility functions can be developed by three methods: heuristic estimation, analytical computation and empirical data. In terms of measuring damage, or the vertical axis of a vulnerability curve, damage index is often used as this is a non-dimensional measure of damage which is defined as repair cost divided by replacement cost. Since it is non-dimensional it can be applied to any building of the relevant type irrespective of building size.

Vulnerability relationships for the project were originally intended to be derived from two damage assessment datasets specific to the East Coast Low event this project focuses on, one provided by the State Emergency Services in NSW (the BEACON data), and the other by the Fire and Rescue NSW Emergency Information Coordination Unit (the EICU data). Both damage datasets cover the 20-22 April 2015 East Coast Low impact around the Dungog NSW area. The BEACON dataset was recorded by SES volunteers and covers the area 35.054°S ≤ *lat* ≤ 31.193°S and 150.361°E ≤ *lon* ≤ 152.927°E, where *lat* and *lon* are the latitude and longitude, respectively. It records a range of attributes such as "property type" or "job received", amongst others. The EICU data was recorded by employees of the Emergency Information Coordination Unit. The data covers an area 33.3978°S ≤ *lat* ≤ 32.3898°S and 151.2658°E ≤ *lon* ≤ 151.972°E, but unlike the BEACON data, it also recorded five damage categories. Vulnerability relationships are derived by plotting the degree of damage reported for residential buildings against the wind and rain hazard specification based on the ACCESS-C3 model output.

Given our findings that the 2015 Dungog case did not provide suitable or sufficient data to derive adequate data-based vulnerability relations, the project resorted to the use of nationally available heuristically derived wind vulnerability functions based on tropical and extratropical cyclone events. The phasing of the BNHCRC companion project "Improving the resilience of existing housing to severe wind events" did not allow us to use improved wind vulnerability relationships from that project as these were not available in time. An additional consideration for this project has been that any vulnerability relation utilised for specific case studies is ultimately intended for national application in order to provide a future national capability of wind impact estimation. This implies that highly locally specific wind vulnerability functions might produce better local results, but may well be less suitable on the continental scale. . With the requirement of a 0.2 second wind gust input (rather than the 3-sec gusts from ACCESS-C3), these functions are not calibrated against ACCESS-C3 wind outputs, but can be related to a 3-sec wind gust (e.g., Holmes and Ginger, 2012) and they provide a starting point from which we can establish the workflow while working towards refined vulnerability functions in the future, once more suitable damage datasets are available.

Heuristic vulnerability functions, as used in this project, are developed by people experienced in observing or estimating loss from natural hazard qualitatively estimating a vulnerability function informed by their experience and any available empirical data. Figure 3 shows an example set of heuristic vulnerability curves for a selection of Western Australian house types exposed to severe wind hazard. Note that the vulnerability curves used are agnostic to the wind direction, and respond only to wind gust magnitudes.

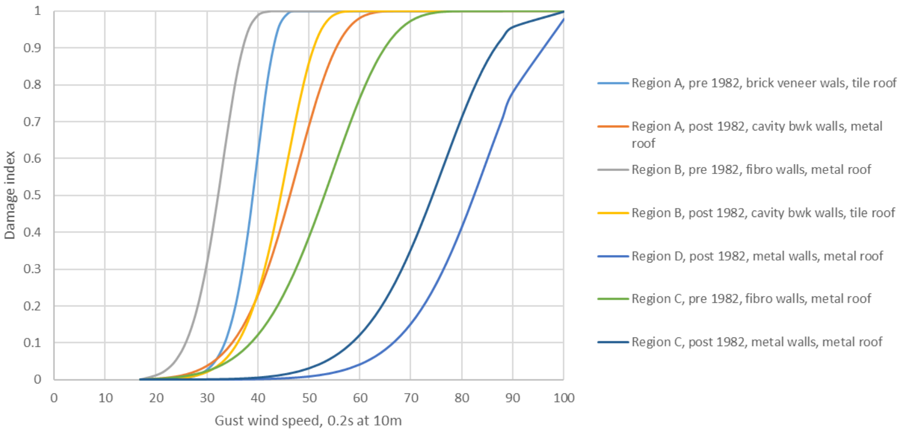


FIGURE 3: HEURISTIC VULNERABILITY FUNCTIONS FOR A RANGE OF WA HOUSE TYPES EXPOSED TO SEVERE WIND HAZARD (BOUGHTON, 2018).

EXPOSURE DATA

Exposure is a term used, in understanding impact and risk, to describe those assets that will be affected by a particular hazard during an event. Exposure information is sourced from the National EXposure Information System (NEXIS) developed by Geoscience Australia (Nadimpalli 2007; Power et al., 2017). NEXIS contains information on building locations, including structural, economic and demographic attributes at the individual building level.

The quality of the NEXIS data is spatially variable; it is reliant on the quality and availability of building specific input data. Where local building survey data is available, the quality of the NEXIS data, at the building level, is better as compared to areas where attributes need to be derived statistically. The statistically derived data areas are representative at an aggregated level but less likely to represent the exact building specific attributes for individual buildings. The NEXIS exposure information for the location of initial interest in this project, Dungog NSW, is statistically derived, which adds uncertainty to any impact prediction for that location.

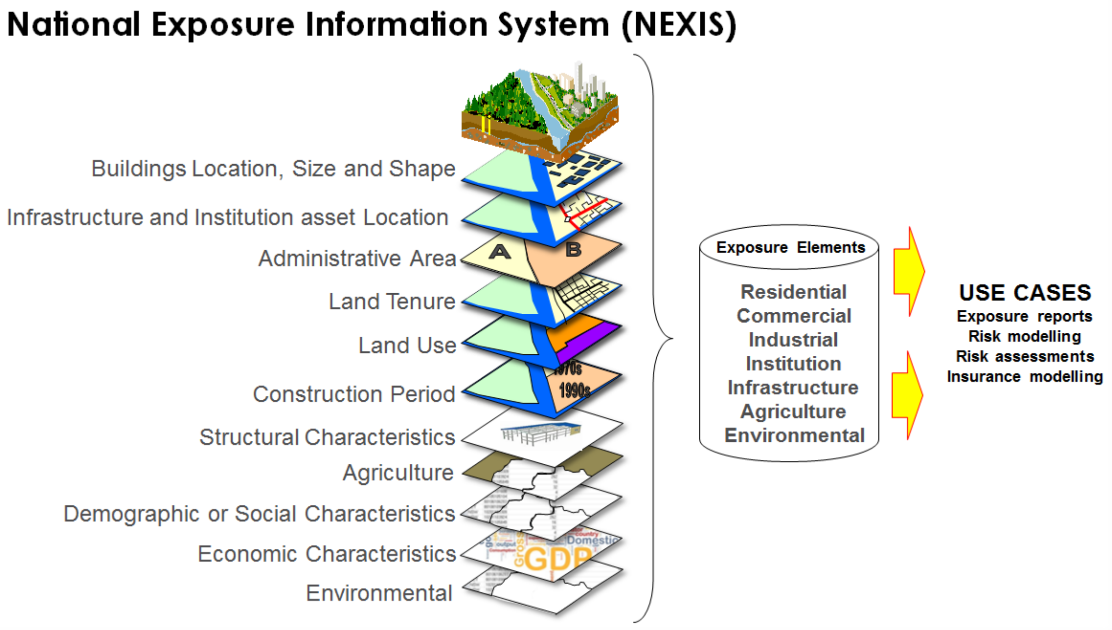


FIGURE 4: SCHEMATIC DEPICTION OF THE NATIONAL EXPOSURE INFORMATION SYSTEM.

To constrain the scope of this pilot study, residential buildings, comprising semi-detached and separate houses, are initially selected as the asset class for the demonstration of the project workflow. NEXIS contains nationally-consistent construction type information for these house types.

THE WORKFLOW

The automated generation of a spatial impact estimates through Geoscience Australia's open source *HazImp* software requires input information on exposure and vulnerability relationships in addition to the ACCESS-C3 based hazard inputs.

The spatial impact estimates are produced by *HazImp* as part of the workflow chain shown in Fig. 5. They are intended to be made available to Bureau of Meteorology forecasters through Visual Weather (the Bureau’s primary operational data display system) and to other end-users in the emergency management sector. A particular benefit of delivery of impact forecasts to Bureau end-users is that severe weather forecasts and warnings can be augmented with impact information to enhance their utility to a variety of end-users, including the emergency response agencies.

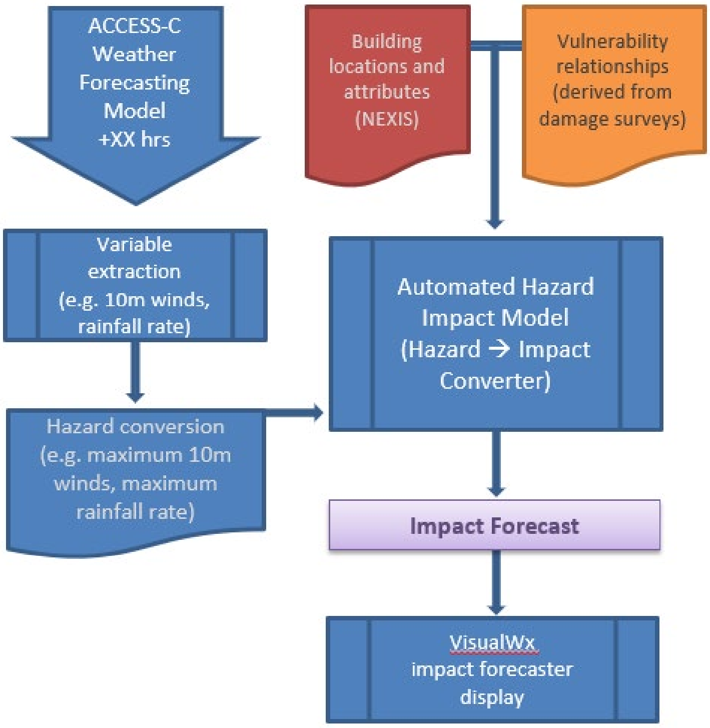


FIGURE 5: IDEALISED PROJECT WORKFLOW FROM HIGH RESOLUTION MODEL OUTPUT TO A SPATIAL DISPLAY OF IMPACTS IN THE BUREAU OF METEOROLOGY'S OPERATIONAL DATA DISPLAY SYSTEM (VISUAL WEATHER).

The selection of ACCESS as the project's hazard forecasting tool, science expertise present within the project, and the available exposure and vulnerability data, has restricted the project to focus on the wind and rain hazard, and to only study their impact on residential buildings as the selected asset class (Fig. 6). The emergency response sector has made it clear to the project that, ultimately, the impact of all meteorological hazards on all asset classes (in particular critical infrastructure) is highly desirable. Such work is possible, but would require an effort that is way beyond the resources available to this project.

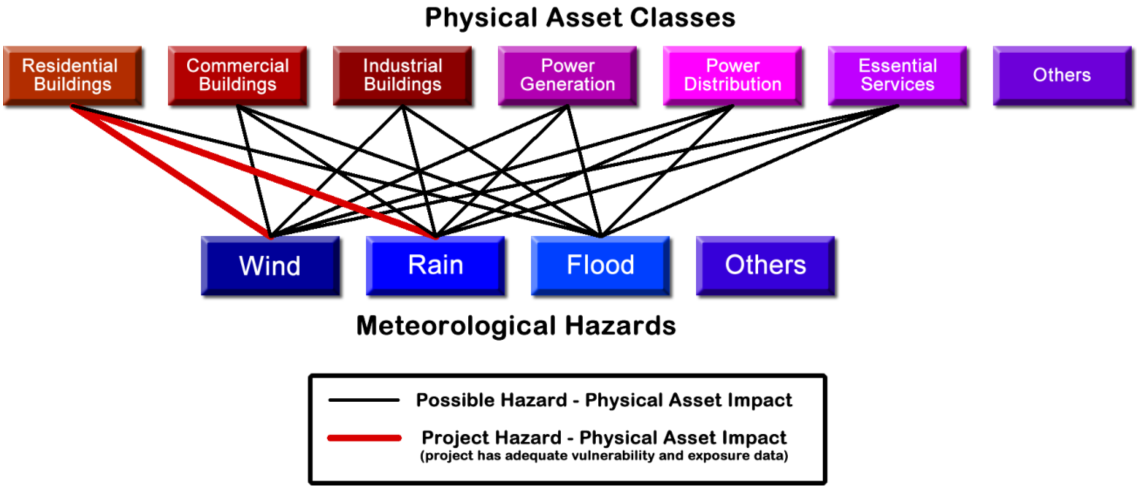


FIGURE 6: SUMMARY OF THE PROJECT'S SELECTION OF HAZARDS AND IMPACTED ASSETS (THE CONNECTIONS MARKED IN RED).

FINDINGS / KEY MILESTONES

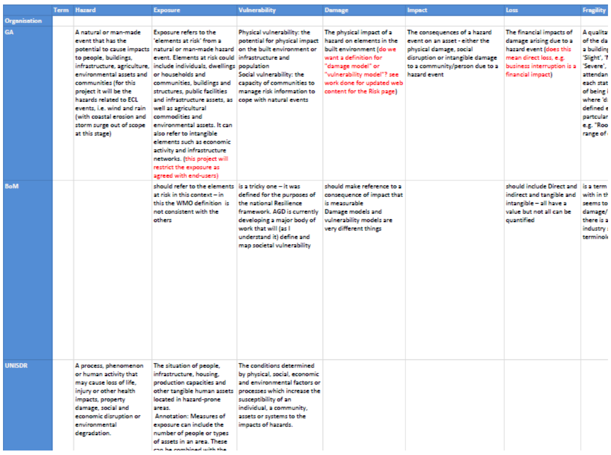
Our core project team was first assembled during the first year of the project, but we experienced a steady stream of project staff arrivals and departures during our 3-year project life cycle due to changing professional circumstances.

Equally, we initially compiled a group of end-users on the basis of demonstrated prior commitment and responsiveness to the project. This end-user group also experienced departures and arrivals, so the listed end-users in this report have not all been involved for the entire duration of the project. The end-users have been affiliated with the Bureau of Meteorology, the State Emergency Services (SES) in Victoria, New South Wales and South Australia, Fire and Rescue New South Wales (FRNSW), the Department for Environment, Water and Natural Resources (DEWNR), the South Australian Country Fire Service (CFS), the Attorney-General's Department's Crisis Coordination Centre (AGCCC), the Department of Fire and Emergency Services in Western Australia (DFES), and the Queensland Department of Fire and Emergency Services (QFES). A complete over view of all the milestones delivered by the project is shown in Appendix A.

The key deliverable of the project over its 3-year life cycle are listed next.

PROJECT GLOSSARY

The diverse background of our team and end-user group, in combination with the multi-disciplinary nature of natural hazard impact assessment necessitated the development of a glossary of terms by the project. Our glossary provides succinct definitions of the terminology used, specific to this project, with the intention of ensuring all participants understand the words and language used throughout reporting and engagement activities. The glossary also contains definitions from a range of other organisations and bodies such as UNISDR or WMO to provide an ability to view the chosen project definitions in the context of pre-existing ones.



	Term	Hazard	Exposure	Vulnerability	Damage	Impact	Loss	Fragility
Organisation								
GA		A natural or man-made event that has the potential to cause impacts to people, buildings, infrastructure, agriculture, environmental assets and communities (for this project it will be the hazards related to ECL events, i.e. wind and rain (with coastal erosion and storm surge out of scope at this stage)	Exposure refers to the 'elements at risk' from a natural or man-made hazard event. Elements at risk could include individuals, dwellings or households and communities, buildings and structures, public facilities and infrastructure assets, as well as agricultural commodities and environmental assets. It can also refer to intangible elements such as economic activity and infrastructure networks. (this project will restrict the exposure as agreed with end-users)	Physical vulnerability: the potential for physical impact on the built environment or infrastructure and population Social vulnerability: the capacity of communities to manage risk information to cope with natural events	The physical impact of a hazard on elements in the built environment (do we want a definition for "damage model" or "vulnerability model"? see work done for updated web content for the Risk page)	The consequences of a hazard event on an asset - either the physical damage, social disruption or intangible damage to a community/person due to a hazard event	The financial impacts of damage arising due to a hazard event (does this mean direct loss, e.g. business interruption is a financial impact)	A qualita of the da a building 'Slight', 'I 'Severe', attendan each stat of being i where 'd defined e partcular e.g. "Roo range of
BoM			should refer to the elements at risk in this context – in this the WMO definition is not consistent with the others	is a tricky one – it was defined for the purposes of the national Resilience framework. AGD is currently developing a major body of work that will (as I understand it) define and map societal vulnerability	should make reference to a consequence of impact that is measurable Damage models and vulnerability models are very different things		should include Direct and indirect and tangible and intangible – all have a value but not all can be quantified	is a term with in th seems to damage/ there is a industry terminol
UNISDR		A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.	The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas. Annotation: Measures of exposure can include the number of people or types of assets in an area. These can be combined with the	The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.				

FIGURE 7: VISUAL SNIPPET OF THE GLOSSARY COMPILED BY THE PROJECT. EACH ROW PROVIDES AN ORGANISATION-SPECIFIC LISTING OF DEFINITIONS FOR THE MORE COMMON TERMS USED IN HAZARD IMPACT MODELLING.

WORKFLOW SETUP

Within the first year of the project we set up an end-to-end (weather model output to spatial impact) workflow across two agencies, the Bureau and GA. Vulnerability information was derived from pre-existing vulnerability relations based on damage assessments from Queensland tropical cyclone case studies, and exposure information was sourced from NEXIS. Hazard predictions (or hindcasts) came from either ACCESS-City (APS3) or the high resolution reanalysis (BARRA-SY). The workflow is depicted in Figure 5.

DERIVATION OF CASE-SPECIFIC VULNERABILITY RELATIONSHIPS FOR THE DUNGOG CASE

Two damage assessment datasets for the 20-22 April 2015 East Coast Low event were sourced and analysed to reveal that the relationship between residential building damage and the driving hazards is complex with a need for the damage reporting to be modified. Through some of our project end-users, these modifications are now being undertaken, which is progress in itself and will, in time, enable new vulnerability relationships for residential housing to be developed for some locations affected by severe weather.

Vulnerability refers to the relationship between severity of impact on an asset from a hazard of given magnitude. Quantitative vulnerability relationships are essential in the estimation of quantitative impact predictions. The key impediments to the derivation of vulnerability relationships for the Dungog event were threefold.

- First, only the EICU data contained a categorical degree of damage (none, minor, major, severe and destroyed). Such a categorisation is needed to relate the damage severity to the magnitude of the associated hazard.
- Second, the wind speeds produced by the Dungog event mostly stayed well below the design wind speeds for newer housing in the Hunter area (34-40 m s^{-1}) and therefore cannot be expected to define the full wind vulnerability relationship.
- In addition, whilst damage was reported in the BEACON and EICU data, it was not possible to determine which hazard(s) caused the damage, i.e. wind or rain or other hazards.

The wind-related damage that did occur during the Dungog event was mostly due to tree fall, rather than direct wind impact on buildings. This 'damage by intermediary' causality chain additionally complicates the derivation of vulnerability relations given tree response to strong winds depends on a multitude of other factors.

An outcome from these findings has been a recommendation to the NSW SES (via the project's end-user, Anthony Day) to amend the damage reporting detail in the BEACON data. **We asked for the inclusion of [a] damage rated by categories and for [b] a linkage for all reported damage to the underlying hazard(s).**

CASE-SPECIFIC VULNERABILITY RELATIONSHIPS FOR DUNGOG NSW: MULTI-HAZARD IMPACTS

Detailed examination of the damage data for the Dungog event also confirmed a well-established view that most impacts are multi-hazard in nature. Fig. 8 demonstrates that the reported total damage in the EICU dataset is not sensibly related to the model-derived wind speed alone, but is the aggregated product of interacting hazards including wind, heavy rain and overland flooding. For example, the damage reports in the top damage category (76-100%, or"destroyed") are not due to the wind hazard, but are related to flooding as a nearby creek rose beyond its banks (Wehner et al. 2015).

Fig. 9 shows the relationship between the EICU damage categories as a function of the 48-hour instantaneous rain rate rainfall maximum. Again, the most severe damage in the 76-100% category occurred at rain rates that were at most intermediate, suggesting that it was not the rai hazard that was responsible for the damage in the highest reported damage category

The derivation of vulnerability relationships from damage assessment data either requires an unambiguous link between the reported damage and a single underlying hazard that caused the damage (as is typically the case for tropical cyclone damage), or it will be necessary to explore the use of multi-hazard predictors to estimate the spatial event-integrated damage pattern in a more statistical sense. Our project did engage in one such exploration, assessing the usefulness of a joint wind & rain damage predictor for the Dungog event (see below).

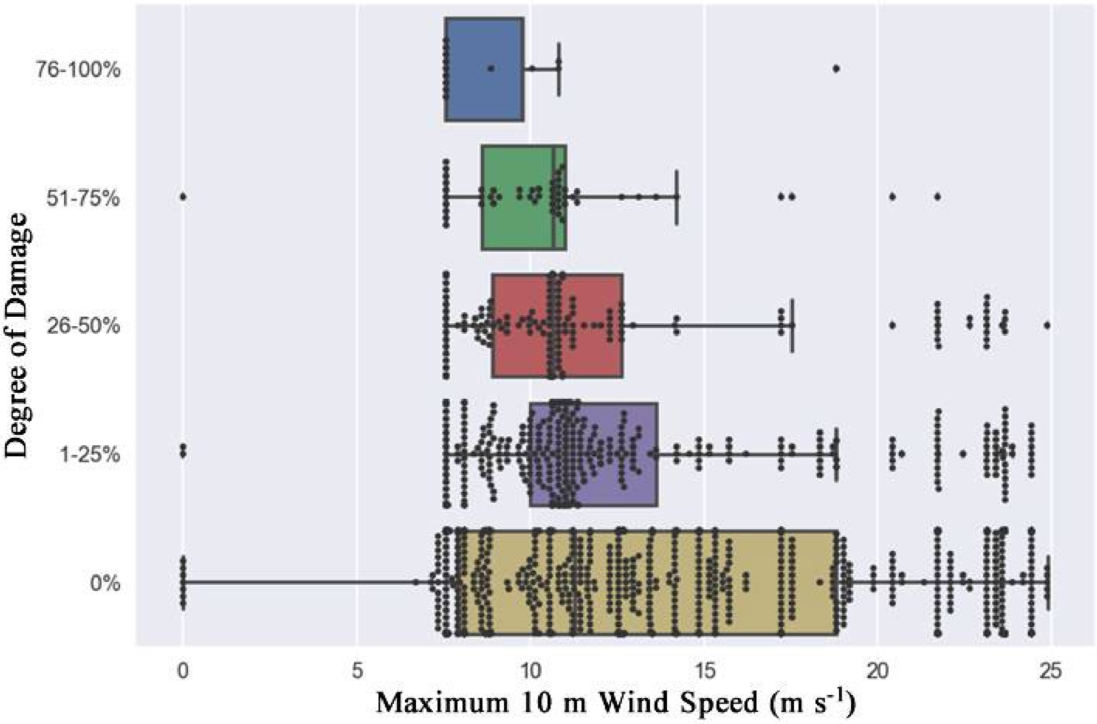


FIGURE 8: 20-22 APRIL 2015 EICU DAMAGE DATA FOR THE TOWN OF DUNGOG (NSW). THE RECORDED BUILDING DAMAGE, CATEGORISED INTO FIVE CLASSES (NONE, MINOR, MAJOR, SEVERE, DESTROYED), IS SHOWN IN RELATION TO THE MATCHING 48-HOUR MAXIMUM 10-M MEAN WIND SPEED FROM ONE INDIVIDUAL ENSEMBLE MEMBER (MEMBER 12) OF A 24-MEMBER HIGH RESOLUTION MODEL RUN ON A 1.3 KM GRID. THE COLOURED BOXES SHOW THE INNER TWO QUARTILES OF THE MODEL WIND DISTRIBUTION FOR EACH DAMAGE CATEGORY.

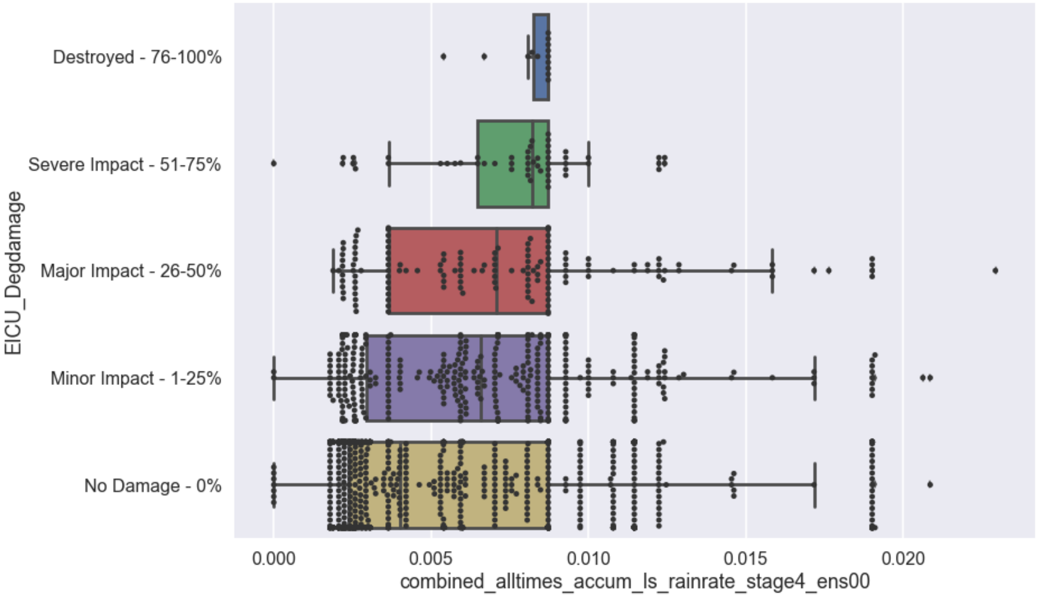


FIGURE 9: AS IN FIG. 8, BUT IN RELATION TO THE MATCHING 48-HOUR MAXIMUM OF THE INSTANTANEOUS RAIN RATE (KG M^{2} S^{-1}) FROM ENSEMBLE MEMBER 0 (THE CONTROL RUN) OF A 24-MEMBER HIGH RESOLUTION MODEL RUN ON A 1.3 KM GRID. THE RAIN RATE IS OUTPUT BY THE MODEL EVERY 30 MINUTES DURING THE PERIOD 00 UTC 20 APRIL 2015 TO 00 UTC 22 APRIL 2015. A CONSTANT RAIN RATE OF 0.01 KG M^{2} S^{-1} WOULD EQUATE TO AN HOURLY RAIN ACCUMULATION OF 36 MM. NOTE THAT THE LABELS ON THE ORDINATE ARE THE SAME AS USED IN FIG. 8, BUT WITH AN ADDITIONAL DESCRIPTOR PROVIDED.

CASE-SPECIFIC EXPOSURE DATA FOR DUNGOG NSW: STATISTICALLY DERIVED DATA

The project has also explored the quality of available exposure information for residential buildings in the Dungog (NSW) area, where such information is derived from surveyed data in neighbouring towns. We gained some important insights into the uncertainties that derived exposure information possesses. Ultimately, the uncertainties of exposure information, of vulnerability relationships and of the hazard predictions generated by the weather prediction models combine into the uncertainty of the final impact outputs.

Akin to the vulnerability relationships, the available exposure information has also been tested for its level of uncertainty. For the township of Dungog, the NEXIS information is statistically derived from known point source data in equivalent nearby towns. The building attributes "wall material" and "roof material" in NEXIS for houses in Dungog are derived from exposure survey results in Newcastle (Dhu and Jones 2002) and Alexandria (Maqsood et al. 2013). The "age" attribute for houses built pre-1982 are sourced from NSW cadastral parcel registration date. The "age" attribute for houses built 1982 and onwards is sourced 75% from NSW median suburb year and 25% from cadastral parcel registration date.

We examined all 856 dwellings in Dungog in a desktop exposure survey (using Google Streetview, aerial and other imagery) and compared the surveyed (actual) wall and roof types to the statistically derived attributes within NEXIS. Fig. 10 shows the degree of agreement between the surveyed and statistically derived house types (a house type is defined as a specific combination of one of ten possible roof types and one of six possible wall types).

Fig. 10 implies that the statistically derived residential building attributes for Dungog do not agree well with the actual attributes on the town scale. This suggests that in areas where residential building attributes need to be derived statistically due to lack of in-situ survey data, wind and rain impacts on such housing can only be meaningfully considered on scales larger than the town scale. This observation is well understood by the NEXIS data custodians. In general, an ameliorating factor is that the NEXIS representation of house types is of higher quality for the more common types. Implementation of an impact forecasting system nationally will require a nationally consistent exposure system which in turn relies on what data each jurisdiction collects and the quality of that data. This decision will become a cost-benefit analysis for each government.

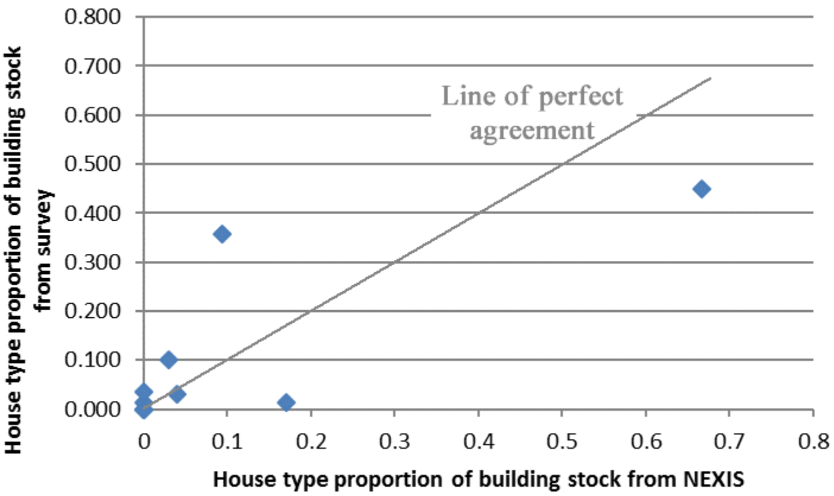


FIGURE 10: RELATIONSHIP OF STATISTICALLY DERIVED NEXIS AND SURVEYED HOUSE TYPES FOR ALL POST-1982 HOUSES IN THE TOWN OF DUNGOG NSW. A "HOUSE TYPE" IS DEFINED AS A COMBINATION OF WALL MATERIAL (10 CATEGORIES) AND ROOF MATERIAL (6 CATEGORIES). NOTE THAT ONLY A SMALL NUMBER OUT OF ALL 60 POSSIBLE HOUSE TYPES IS ACTUALLY PRESENT IN DUNGOG.

WORKFLOW ESTABLISHED

During 20-21 September, early during the second year of this project, Serena Schroeter and Craig Arthur teamed up in the Bureau's Head Office in Melbourne to collaborate on the removal of the residual hurdles in the end-to-end workflow. This included:

- modifying *HazImp* code to ingest netCDF files (data format for ACCESS NWP)
- modifying *HazImp* to produce geospatial data output to enable impact data to be visualised in geographic information systems and other applications (including Visual Weather).

The first ever spatial impact output from Geoscience Australia's Hazard Impact Model displayed through the Bureau primary operational data viewer, Visual Weather, is shown in Fig. 11.

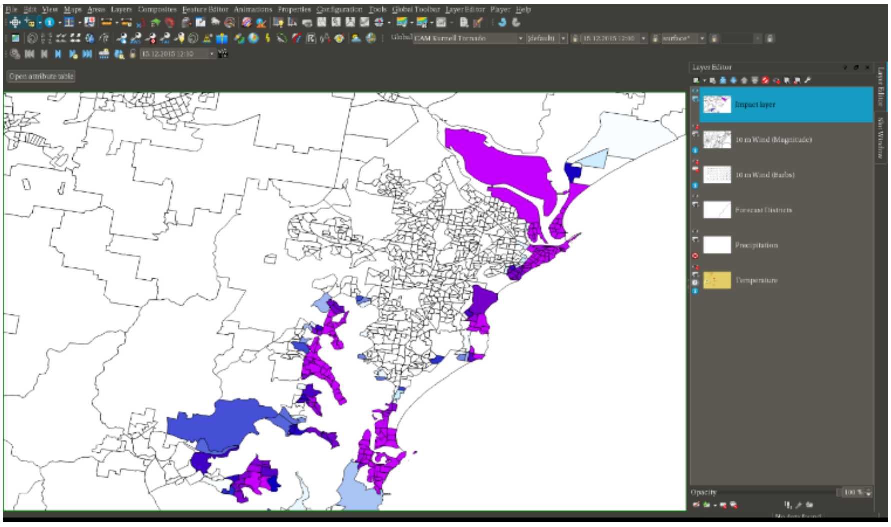


FIGURE 11: FIRST SAMPLE OF A SPATIAL IMPACT OUTPUT FROM HAZIMP DISPLAYED IN THE BUREAU'S VISUAL WEATHER DATA VIEWER. THE UNDERLYING HAZARD IS THE WIND SPEED 10 METRES ABOVE GROUND LEVEL AS PRODUCED FROM ONE OF THE ENSEMBLE MEMBERS FOR THE 20-22 APRIL 2015 DUNGOG EAST COAST LOW EVENT ON A 1.3 KM GRID. THE IMPACT RATING (COLOUR) IN EACH POLYGON IS DERIVED FROM AN AVERAGE ACROSS MULTIPLE DAMAGE INDICES COMPUTED FOR EACH INDIVIDUAL RESIDENTIAL BUILDING LOCATED WITHIN THE POLYGON.

REQUEST FOR MORE DETAILED DAMAGE ASSESSMENT DATA

BEACON Data Reporting Upgrade Request: The project has approached SES NSW (through Tony Day, NSW SES) requesting some modifications of the BEACON Damage Assessment template. The two main drivers of this change request are the project's need to (a) categorise damage by degree of severity, and (b) attribute reported damage to the hazard(s) that caused that damage. No progress has been made on the implementation of the requested modifications due to the low priority within NSW SES, and the absence of support for resources to perform the required work to enhance the BEACON system.

DEMONSTRATION FOR EXTREME WEATHER DESK FORECASTERS

On 20 September 2018 the project engaged several forecasters from the Bureau's Extreme Weather Desk and the Victorian Regional Office. We demonstrated the first samples of spatial impact graphics to draw out opinions on their usability and how this new information could enrich the existing forecast products. All consulted users were remarkably eager to gain access to the spatial impact information, but the incorporation into forecasts was a more difficult question to answer at this early stage.

FIRST MILESTONE VARIATION

As reported in previous quarterly reports, investigations during the first year of the project made it increasingly clear that the available damage assessment data for the 20-22 April 2015 Dungog East Coast Low event did not allow the project to relate the level of residential building damage to the magnitude of either the wind or the rain hazard in isolation. The reasons are that most damage is caused by more than a single hazard, and that the best available damage data do not link the reported damage to the hazard that caused it. Consequently, in consultation with the BNHCRC, we have modified some of the milestones to accommodate the above findings. The varied milestones for project year two are included in Appendix A.

IDENTIFICATION OF ADDITIONAL WIND & RAIN-PRODUCING EVENTS

The selection of cases exhibiting strong surface winds and heavy rain has been strongly constrained by the co-availability of damage assessment and high resolution NWP model data. First, to establish relationships between hazard magnitude and damage magnitude, only Emergency Information Coordination Unit (EICU) data can be used as damage data, and only since 2015 when the EICU data in their current high quality form was first collected. Second, it is beyond the project's capacity to produce any further customised high-resolution ACCESS-City model runs for cases beyond the April 2015 Dungog event given the complexity of the ACCESS modelling system and the expertise required to operate the model. We therefore rely on existing high resolution model runs provided by the high resolution reanalysis BARRA. While BARRA provides reanalyses on 1.5 km grids for approximately the previous two decades, the high-resolution grids are only set up in the four areas outlined in black in Fig. 12.

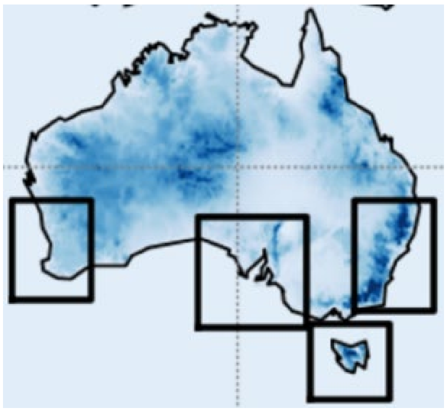


FIGURE 12: DOMAINS OF THE FOUR BARRA HIGH-RESOLUTION (1.5 KM) REANALYSIS PRODUCED BY THE BUREAU. THE FOUR DOMAIN NAMES, FROM EAST TO WEST, ARE BARRA-SY, BARRA-TA, BARRA-SA AND BARRA-WA.

Large-scale wind and rain cases had to be sourced inside the BARRY-SY domains during the four years 2015-2018 (see above), and be equipped with an adequate number of EICU damage reports, which narrowed the selection to the following three cases (Table 1). Further examination of the two additional cases revealed, however, that the BARRA-SY wind hazard representation was not suitable for non-probabilistic wind impact modelling. For example, in the December 2015 Kurnell event, wind damage was mostly limited to the narrow swaths of a number of severe thunderstorms. Storms of that small scale (compared to an extratropical low) are not predicted at the right place and right time by most high-resolution models including BARRA-SY. This created a mismatch between hazard placement and damage locations.

TABLE 1: LIST OF SEVERE WIND / RAIN EVENTS SUITABLE FOR HIGH RESOLUTION MODELLING WHERE EICU AND BARRA-SY DATA ARE AVAILABLE SIMULTANEOUSLY.

Year	Event Name	Event Type	Approximate number of houses damaged	Total number of EICU records
April 2015	Dungog ECL	Wind / Rain / Flood	252	2000
December 2015	Kurnell Tornado	Wind / Tornado from Strong Convective Storms	167	135
June 2016	Picton, Narrabeen, Bankstown	East Coast Low (coastal erosion)	229	1400

SYSTEMATIC PRODUCTION OF HAZARD GRIDS

The project produced range of wind and rain hazards grids that was intended to allow an optimal way of devising hazard combination choice for the estimate of combined wind and rain impacts on residential properties. The twenty possible combinations from five rainfall hazard proxy grids and the four wind hazard proxy grids are listed in Table 2.

TABLE 2: NINE HAZARD TYPES (5 FOR RAINFALL IMPACT, 4 FOR WIND IMPACT) ARE EXTRACTED FROM THE HIGH-RESOLUTION REANALYSIS DATASET BARRA-SY FOR 3 WIDESPREAD WIND AND RAIN EVENTS IN DUNGOG (20-22 APRIL 2015), KURNELL (16 DECEMBER 2015) AND NARRABEEN (4-6 JUNE 2016).

Wind predictor (right) and rain predictor (below)	Point Surface Wind Gust (PSWG)	Point Surface Mean Wind (10-minute mean; PSMW)	Neighbourhood (40 km radius) Surface Wind Gust (NSWG)	Point Gradient-level (900 hPa) Wind Speed (PGWS)
Point Instantaneous rain rate or accumulation (PIRR)	Predictor Combination 1	Predictor Combination 2	Predictor Combination 3	Predictor Combination 4
Point 1-hr accumulation (P1RR)	Predictor Combination 5	Predictor Combination 6	Predictor Combination 7	Predictor Combination 8
Point 6-hr accumulation (P6RR)	Predictor Combination 9	Predictor Combination 10	Predictor Combination 11	Predictor Combination 12
Point Total Event accumulation (PTEA)	Predictor Combination 13	Predictor Combination 14	Predictor Combination 15	Predictor Combination 16
40 km radius neighbourhood accumulation (N1RR)	Predictor Combination 17	Predictor Combination 18	Predictor Combination 19	Predictor Combination 20

The hazard grids extracted from BARRA-SY broadly consider rain and wind at a point location over varying timescales. One neighbourhood maximum value is included for each hazard type (N1RR; NGWS) to study the effects that each model grid point experiences the maximum hourly rain rate / wind gust value that exists in a neighbourhood within a 40 km radius. A 40 km neighbourhood radius may seem excessively large, but in particular for multi-day lead times NWP model placement errors can be of similar spatial scale (or larger), so that this large radius needs to be understood as an attempt to accommodate model errors of similar magnitude.

All grids for the Dungog and Kurnell cases could be produced, but the BARRA-SY reanalysis runs for the Narrabeen case in June 2016 did not complete on time for our analysis.

PRELIMINARY RAIN IMPACT MODEL WORKFLOW

The central impact production code, *HazImp*, was configured to accept BARRA-SY 1.5 km reanalysis rainfall grids in addition to the previously used wind grids. This allows *HazImp* to produce rainfall impacts, given the additional specification of rainfall vulnerabilities of residential property. *Unlike wind vulnerabilities, much less is known about the susceptibility of residential buildings to water ingress from high-intensity rainfall.* To demonstrate the impact forecasting workflow works for rainfall, the existing wind vulnerabilities were rescaled to function as vulnerabilities to hourly rain rates. The scientific validity of this highly idealised approach is questionable, and these first guess functions serve the initial purpose of executing a rain hazard workflow end to end. Figure 13 shows the resulting impact forecast product for the 20-22 April 2015 East Coast Low, with impacts aggregated to SA1 level.

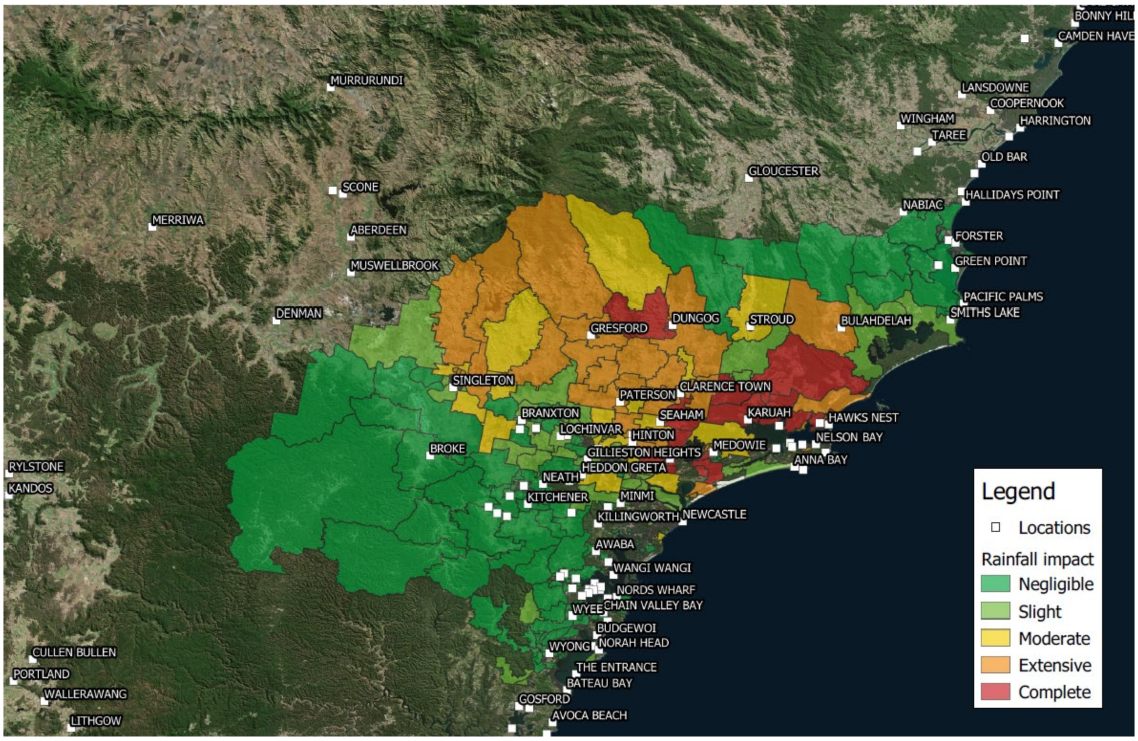


FIGURE 13: MEAN RESIDENTIAL BUILDING LOSS RATIO DUE TO THE RAIN HAZARD, AGGREGATED TO SA1 POLYGONS FOR THE 20-22 APRIL 2015 DUNGOG EAST COAST LOW EVENT. THE MEAN LOSS RATIO IS CATEGORISED INTO NEGLIGIBLE (< 0.15%), SLIGHT (0.15-0.5%), MODERATE (0.5-1.0%), EXTENSIVE (1.0-2.0%) AND COMPLETE (> 2%). THE RAIN HAZARD IS THE EVENT MAXIMUM HOURLY RAIN ACCUMULATION SOURCED FROM THE 1.5 KM BARRA-SY REANALYSIS DATASET AS PRODUCED BY THE BUREAU OF METEOROLOGY.

PROJECT JOINED WMO TASK TEAM

During its second year, the project has joined the World Meteorological Organisation (WMO) Task Team on Human Impacts, Vulnerability and Risks led by Brian Mills from Environment and Climate Change Canada (ECCC; https://www.wmo.int/pages/prog/arep/wwrp/new/high_impact_weather_project.html). Through this membership the project gained easier access to impact prediction groups and experts around the world, and we were also able to more easily solicit feedback on our own work by the international community as part of quality benchmarking.

REVISION OF SELECTED ASSET CLASS FOR IMPACT MODELLING

On 7 March 2019 the project engaged in a fruitful discussion with the lead end-user (Roger Mentha, FRNSW) and Anthony Day (NSW SES) in Sydney. Discussion focused on the scope of analysis possible in the project, and the Strategic Priorities of NSW SES in emergency response. A key priority for NSW SES is the protection of critical infrastructure (CI) and community assets essential to community survival in an emergency incident. Previous activities at Geoscience Australia indicate that engagement with CI owners and operators presents a major challenge to including elements of CI in the impact modelling workflow. The project suggests to open a dialogue involving SES NSW, FRNSW, this project and BNHCRC via the NSW State Emergency Management Committee (SEMC) to explore the design of a potential future project with an ability to focus on impact forecasts for elements of critical infrastructure.

TESTING A TWIN-HAZARD PREDICTOR FOR WIND AND RAIN

The literature review, and informal communications with other researchers working on impact-based forecasting applications have shown that the majority of physical impacts are not the result of a single hazard, but that multiple hazards interact to drive hazard. In this pilot project we are restricted to two meteorological hazards that can be readily derived from NWP products: wind and rain. For these interacting hazards, a pertinent question is whether some combination of wind gust strength and rain rate can deliver a robust predictor of damage to residential houses.

We employed the Quadratic Discriminant Analysis (QDA) as a methodology that yields the probability of housing damage for a range of combinations of wind speed and rain rates as listed in Table 2. Again, the event impact data used are the Emergency Information Coordination Unit (EICU) rapid damage assessment data for the 20-22 April 2015 Dungog East Coast Low event. The spatial hazard estimations are sourced from the Bureau's Reanalysis, BARRA-SY.

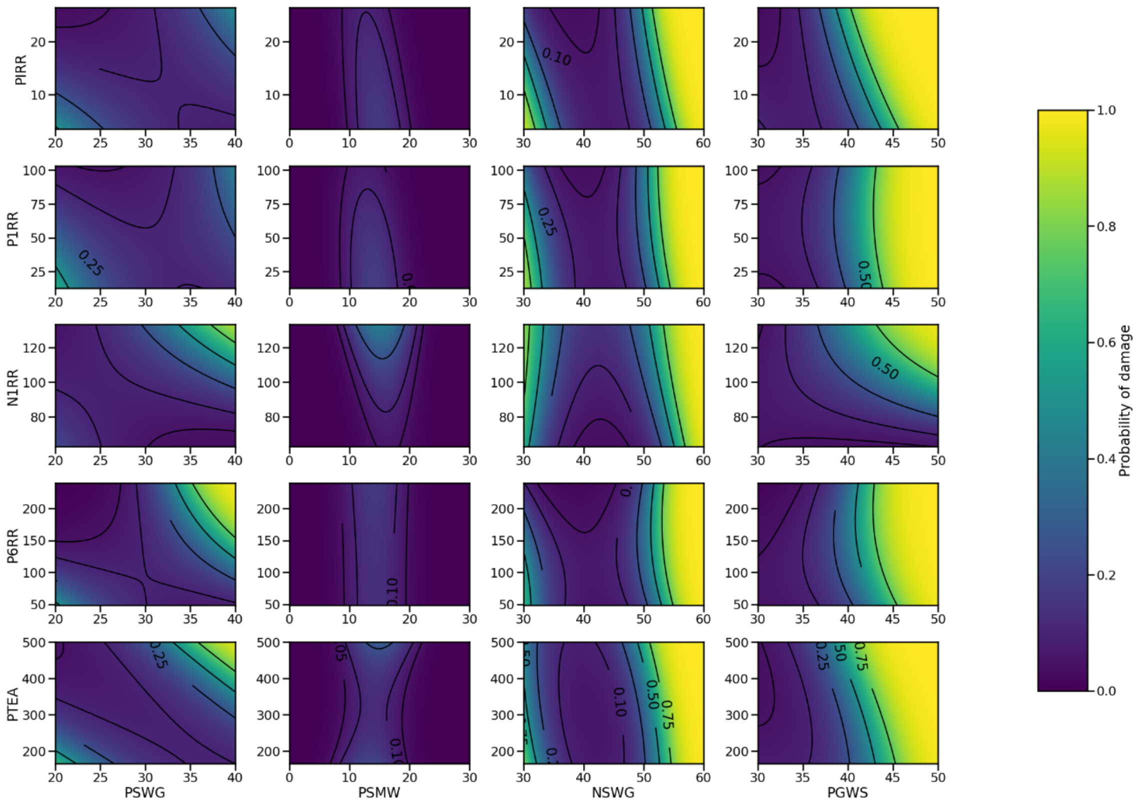


FIGURE 14: THE PROBABILITY OF BUILDING DAMAGE ARISING DUE TO A COMBINATION OF RAINFALL AND WIND HAZARD PREDICTORS BASED ON A QUADRATIC DISCRIMINANT ANALYSIS (QDA). THE ROWS SPECIFY DIFFERENT TYPES OF RAIN HAZARD PREDICTORS: 1-HOUR RAINFALL ACCUMULATION AT A POINT (P1RR), 1-HOUR RAINFALL ACCUMULATION IN A 40 KM NEIGHBOURHOOD (MAXIMUM VALUE WITHIN THAT NEIGHBOURHOOD; N1RR), 6-HOUR RAINFALL ACCUMULATION AT A POINT (P6RR), EVENT (72-HOUR) RAINFALL ACCUMULATION AT A POINT (PTEA). THE COLUMNS SPECIFY 10-M 3-SECOND WIND GUST AT A POINT (PSWG), 10-M ~10 MINUTE MEAN WIND (PSMW), NEIGHBOURHOOD MAXIMUM 10-M 3-SECOND WIND GUST (NSWG), 900-HPA (~1 KM ABOVE THE GROUND) WIND SPEED AT A POINT (PGWS). ALL PREDICTORS (EXCEPT FOR PTEA) ARE EVENT MAXIMA FOR THE 72-HOUR PERIOD FROM 03 UTC 19 APRIL 2015 TO 03 UTC 22 APRIL 2015. "DAMAGED" IS DEFINED AS EICU DAMAGE RATINGS IN THE CATEGORIES MODERATE, EXTENSIVE OR COMPLETE. SOLID BLACK CONTOUR INTERVALS FOR THE DAMAGE PROBABILITIES ARE 0.25.

This QDA analysis turned out to be highly sensitive to the input data, which in our case is limited to those events where we have access to qualitative damage survey data and the corresponding BARRA-SY data. Adding the Kurnell tornado case to the above analysis changed the outcomes dramatically, raising serious concerns about the robustness of the relationship. This inability to derive robust dual-predictor damage probabilities formed the bases for a second scope review within the project. Unlike for wind, no useable rain ingress vulnerability functions exist in Australia (or elsewhere, to our knowledge). With such first guess vulnerabilities and the EICU damage data as they are, the inclusion of rain impacts seems to be beyond our reach for now.

PERTH RAF & DFES-HOSTED END-USER WORKSHOP

The Extreme Weather Research Advisory Forum (RAF) for 2019 took place at the Department of Fire and Emergency Services (DFES) in Perth on 30 July 2019. After recalling the current status of the work, the project presented four potential options for utilisation work to the stakeholders present:

1. Creation of a Crisis Coordination Centre (CCC) product akin the GA's tropical cyclone impact product

2. A testbed for the real-time appraisal and validation of the wind / rain spatial impact forecasts
3. Application of the project workflow on selected critical infrastructure
4. Exploration and validation of new measures of physical impacts on residential buildings

An end-user workshop with ~17 attendees was held at the same venue (DFES) on 31 July 2019. End-users were taken through the project workflow in a manual fashion, where the individual layers of the quantitative impact prediction were made available one by one to encourage a subjective human overlay of all layers to arrive at an impact prediction. At the end the automatically calculated spatial impact pattern was compared to the human impact estimates. The intense exposure to the impact forecasting workflow equipped the end-users present to comment more meaningfully on some of the project's hard questions such as the need for additional information to be provided by the workflow, or desirable adjustments in project outputs for easier utilisation by end-users. A more detailed report on the end-user workshop has been submitted to the BNHCRC.

REFINED VALIDATION METHODOLOGY DEVELOPED AND INDICATIVE RESULTS GENERATED FOR THE WIND IMPACT MODEL

Figure 15 shows a spatial plot of the distribution of EICU-reported damage using the same polygon size as our impact forecasts. The general expectation would be that polygons (SA1 areas[1]) with a predicted high impact will show a larger density of damage assessments than predicted low impact areas.

Driven by high resolution 10-m 3-sec wind gust field (PSWG) from BARRA-SY for the Dungog event (20-22 April 2015), the work flow produced a spatial wind impact image coloured by the average loss ratio in each SA1 area segment on the map (a measure of the average wind damage per house in each area). The placement of the coloured dots in Fig. 15 indicates that the EICU damage surveys took place in selected individual towns, so that the absence of coloured dots in some "high impact" areas is not necessarily indicative of an absence of damage. The project has also been pursuing the use of SES damage data due to their more extensive coverage, and despite the lack of categorisations of the damage magnitude. We used the callout density (number of callouts per area) as a proxy for the damage category.

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[1] http://www.abs.gov.au/websitedbs/D3310114.nsf/home/Australian+Statistical+Geography+Standard+(ASGS)

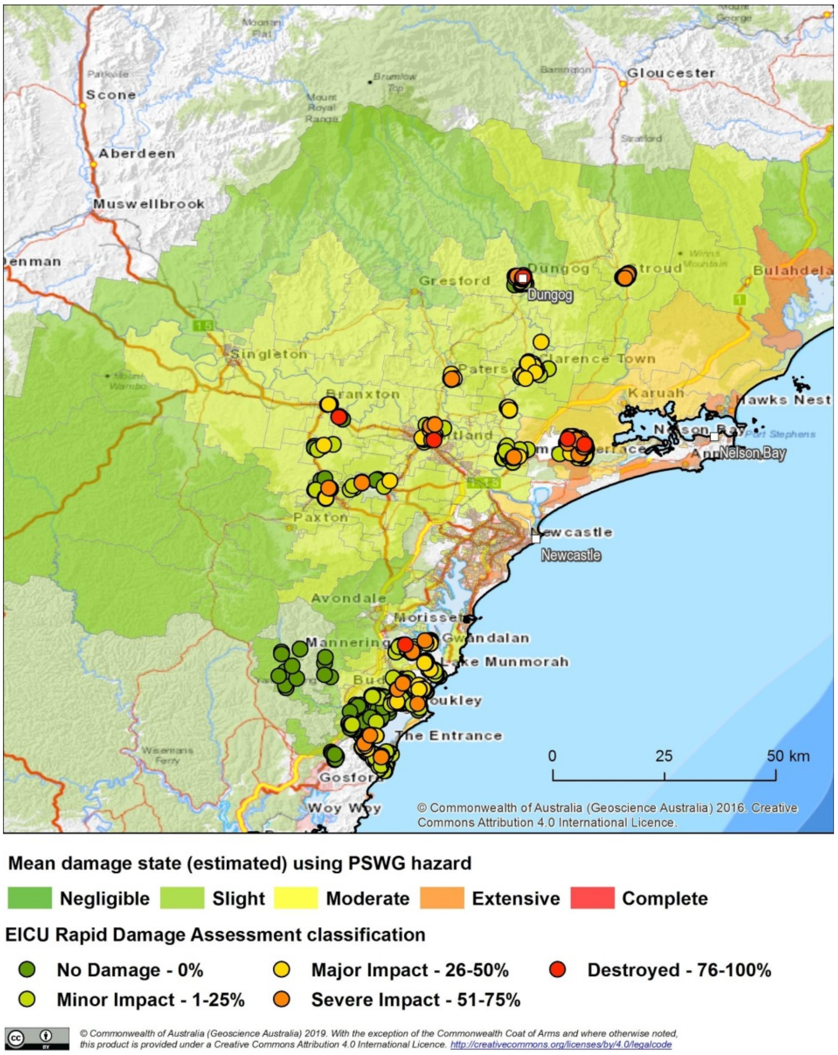


FIGURE 15: MODEL PREDICTION OF THE SURFACE GUST WIND IMPACT EXPRESSED AS A "MEAN DAMAGE STATE" FOR THE 20-22 APRIL 2015 HUNTER VALLEY EAST COAST LOW EVENT. THE OVERLAID POINTS ARE INDIVIDUAL EICU DAMAGE ASSESSMENTS, COLOURED ACCORDING TO THE SURVEYED DAMAGE STATE.

Despite the shortcomings of the currently available damage assessment data for the purposes of quantitative wind impact modelling for residential buildings, the project found a somewhat labour-intensive but viable approach to evaluate how our quantitative impact forecast for the 20-22 April 2015 East Coast Low event verifies against a hazard-only impact forecast.

The absence of information in the damage data that relates the recorded damage consistently and reliably to the underlying hazard that caused it has partially been offset through a sophisticated data filtering approach applied to the Emergency Coordination Information Unit (EICU) data. Damage records were assessed individually and manually, so that any entries stating water levels, flooding, tree damage (and any other damage drivers that are not wind) could be removed. The BARRA-SY reanalysis rainfall was used to further remove all those damage entries where the reanalysed rainfall exceeded certain thresholds that are commonly relatable to overland flooding. We decided not to explicitly retain all those observed damage records where the reanalysis showed surface wind gusts in excess of damaging thresholds (e.g., 50 knots) as such a filtering method would bias the retained damage assessment records in favour of the reanalysis-based impact forecast results themselves.

Damage observations and forecasts were divided into three categories each (minor, moderate, major; Table 3). The filtered damage assessment data were finally aggregated to SA-1 areas so they became comparable to the SA-1 aggregated impact forecasts from our impact model.

TABLE 3: THRESHOLDS CHOSEN TO CATEGORISE THE EMERGENCY INFORMATION COORDINATION UNIT (EICU) AND THE MODEL-PRODUCED SA1 MEAN STRUCTUREAL LOSS RATIO INTO 3 (5) DAMAGE CATEGORIES SUITABLE FOR THE MULTI-CATEGORY FORECAST TO FOLLOW.

Observations

	Integer	
EICU damage state	**5 Cat**	**3 Cat**
No Damage – 0%	1	1
Minor Impact – 1-25%	2	2
Major Impact – 26-50%	3	
Severe Impact – 51-75%	4	3
Destroyed – 76-100%	5	

Forecast

	Integer	
SA1 mean structural loss ratio	**5 Cat**	**3 Cat**
[0.00,0.02)	1	1
[0.02,0.10)	2	2
[0.10,0.20)	3	
[0.20,0.50)	4	3
[0.50,1.00]	5	

A variety of verification scores were computed. The Gerrity Score (Jolliffe and Stephenson 2003, Gerrity 1992) was chosen as the primary assessment metric as it has a refined ability to penalise the degree of category mismatch between model and observations for a multi-category forecast. The skill of the quantitative impact forecast needs to be seen in comparison to the much easier straight wind forecast as a reference approach (Fig. 16).

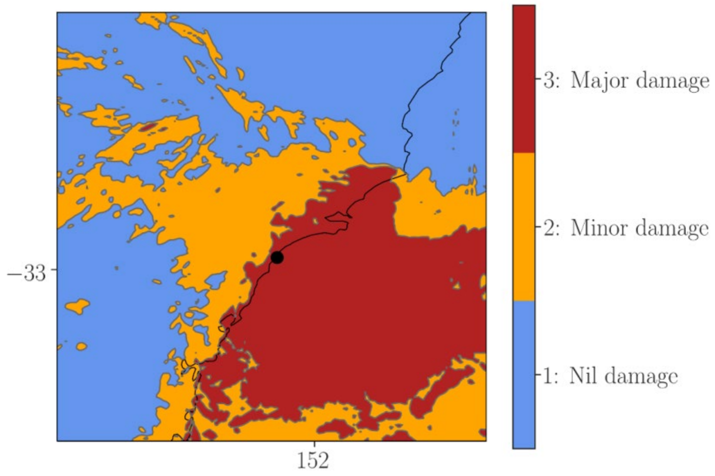


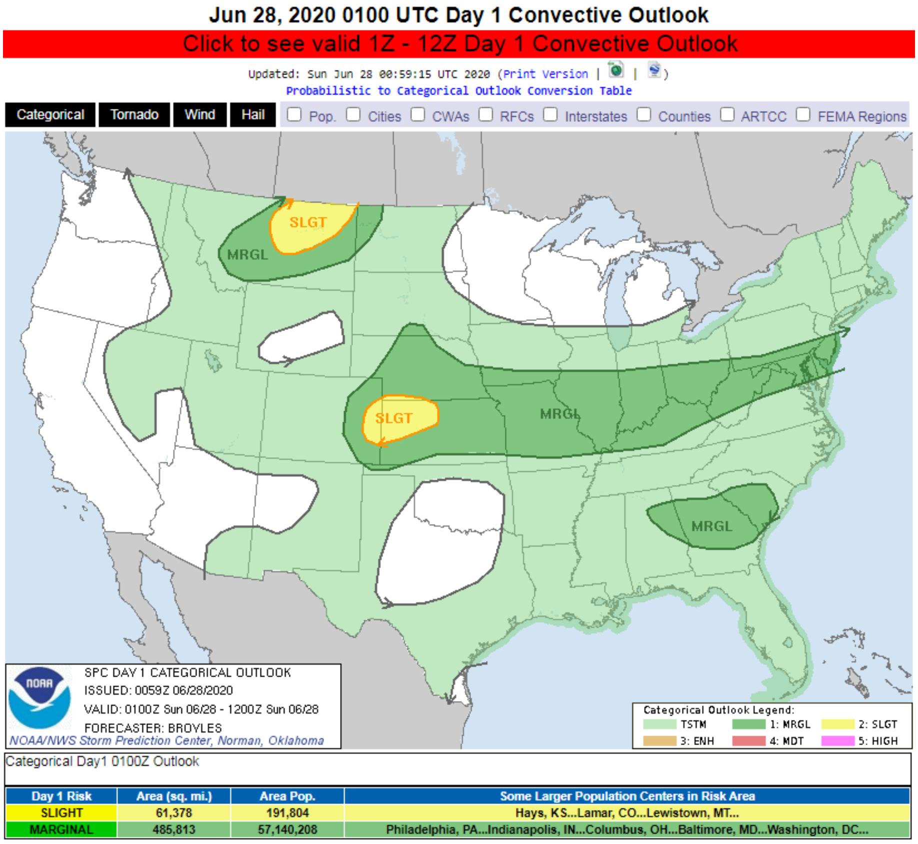
FIGURE 16: SIMPLE REFERENCE "IMPACT" FORECAST BASED SOLELY ON THE 20-22 APRIL 2015 DUNGOG EVENT MAXIMUM 10-M WIND GUSTS FROM THE BARRA-SY HIGH RESOLUTION REANALYSIS, EXPRESSED AS A 3-CATGEORY FORECAST. THE WIND DAMAGE CATEGORIES ARE A SIMPLE MAPPING FROM THE MAXIMUM GUST SPEEDS: NIL (< 25 M S^{-1}), MINOR (25-34 M S^{-1}), MAJOR (> 34 M S^{-1}).

This comparison which utilises the subjectively filtered EICU damage data reveals a clear skill increase due to the inclusion of exposure and vulnerability information, i.e. the skill gain due to enhancing a hazard forecast to an impact forecast. In particular a calibrated version of the full impact forecast (where the SA1 mean structural loss ratio boundaries between the three categories were set in such a manner that they deliver optimal skill) produced much better skill scores compared to the simple wind-only driven impact forecast. Our results for the 20-22 April 2015 Dungog case revealed that the impact forecasts substantially outperformed the plain re-mapped wind hazard forecast in Fig. 16 when assessed using the EICU damage data processed as described above. Therefore this project has demonstrated (for one case) that the substantial effort required to pursue quantitative wind impact forecasts **can** lead to additional value compared to hazard-based wind damage estimates.

IMPACT FORECASTING REVIEW PAPER SUBMITTED TO AJEM

During the second project year a manuscript of a review paper on impact-based forecasting studies and systems was completed. This work package was led by Serena Schroeter, and a lot of collective effort had gone into the compilation and review of this paper. Consultations and reviews took place within the project, within GA and the Bureau, and internationally with the Weather Impact Team at the UK Met Office. The paper was initially submitted to Weather, Community and Society (WCAS), but was not accepted by the journal.

During its second and third year, the project overhauled the initial draft of the review paper on published systems that aim to produce impact-flavored hydrometeorological forecasts. The paper makes an attempt to present a hierarchy that allows us to line up the various systems from 'almost pure hazard' all the way across to fully quantitative hazard impact models.
Most 'impact' forecasts that we surveyed only take modest steps beyond the forecast of the pure hazard. These steps may entail the provision of additional information such as the population size affected by a hazard. Such information can be seen as a crude proxy for specific types of exposure or vulnerability characteristics, and its provision requires little extra effort beyond the hazard forecast itself. Models that use such stand-alone pieces of exposure or vulnerability proxies are also referred to as layered models, where the end-user is left with the task to integrate the separate layers of information to estimate the final impact. An example of a layered impact model is the *Convective Outlook* product from one of the national weather forecast centres operated by the National Oceanic and Atmospheric Administration in the U.S., the Storm Prediction Center (SPC). Fig. 17 shows an example how the simple addition of potentially affected population numbers (a proxy for exposure) is used as a first step towards gauging the impact of a hazard-driven polygon outlining likely areas for severe convective storms.



Jun 28, 2020 0100 UTC Day 1 Convective Outlook

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Updated: Sun Jun 28 00:59:15 UTC 2020 (Print Version | |)

Probabilistic to Categorical Outlook Conversion Table

SPC DAY 1 CATEGORICAL OUTLOOK
ISSUED: 0059Z 06/28/2020
VALID: 0100Z Sun 06/28 - 1200Z Sun 06/28
FORECASTER: BROYLES
NOAA/NWS Storm Prediction Center, Norman, Oklahoma

Categorical Outlook Legend:
TSTM
1: MRGL
2: SLGT
3: ENH
4: MDT
5: HIGH

Categorical Day1 0100Z Outlook

Day 1 Risk	Area (sq. mi.)	Area Pop.	Some Larger Population Centers in Risk Area
SLIGHT	61,378	191,804	Hays, KS...Lamar, CO...Lewistown, MT...
MARGINAL	485,813	57,140,208	Philadelphia, PA...Indianapolis, IN...Columbus, OH...Baltimore, MD...Washington, DC...

FIGURE 17: THE 'DAY 1" CONVECTIVE OUTLOOK PRODUCT FROM THE STORM PREDICTION CENTER IN THE UNITED STATES. THE CATEGORICAL AREAS MARKED 'SLIGHT' AND 'MARGINAL' ARE AREAS AT ENHANCED RISK OF BEING IMPACTED BY CONVECTIVELY GENERATED HAZARDS SUCH AS STRONG WINDS, LARGE HAIL OR TORNADOES. NOTE THE AREA SIZE AND POPULATION NUMBERS POTENTIALLY AFFECTED BY THESE AREAS OF ENHANCED RISK.

A second approach to a simple impact estimate is to put hazard forecasts in their climatological context. Often physical impacts are not so much controlled by the absolute magnitude of a hazard, than they are by how 'unusual' the occurrence of a certain hazard magnitude is at a given geographic location.

At the impact end of the hazard-impact spectrum are the quantitative hazard impact models. Examples of these are the Vehicle Overturning Model (VOT; Hemingway and Gunnavan 2018; Hemingway et al. 2014) and the Surface Water Flooding Model (SWF; Aldridge et al. 2016; Hemingway and Gunawan 2018), both developed at the UK Met Office in conjunction with their partners. These models quantify connections between predicted spatial wind speeds and the likelihood of trucks overturning (for VOT), or predicted precipitation and the likelihood of overland flooding (for SWF). Such models are difficult to build due to the requirement to quantify a range of processes that aggregate to form the final impact. They also require extensive datasets to quantify exposure of assets to the hazard, and to quantify the vulnerability of those assets to the hazard.

In this context, our project is firmly positioned near the 'difficult' end of impact forecasting as it also attempts to quantify the role of hazard, exposure and vulnerability.

EXTEND WIND IMPACT FORECAST PILOT TO ALLOW MULTIPLE FORECAST LEAD TIMES

A strong extratropical cyclone that affected southwest Western Australia on 24 May 2020 was selected to test the influence of wind gust strength variations in successive model runs on the wind impact output (see http://www.bom.gov.au/cgi-bin/charts/charts.view.pl?idcode=IDX0102&file=IDX0102.202005241800.gif for the Bureau of Meteorology's Mean Sea Level Pressure Analysis at their peak of the event).

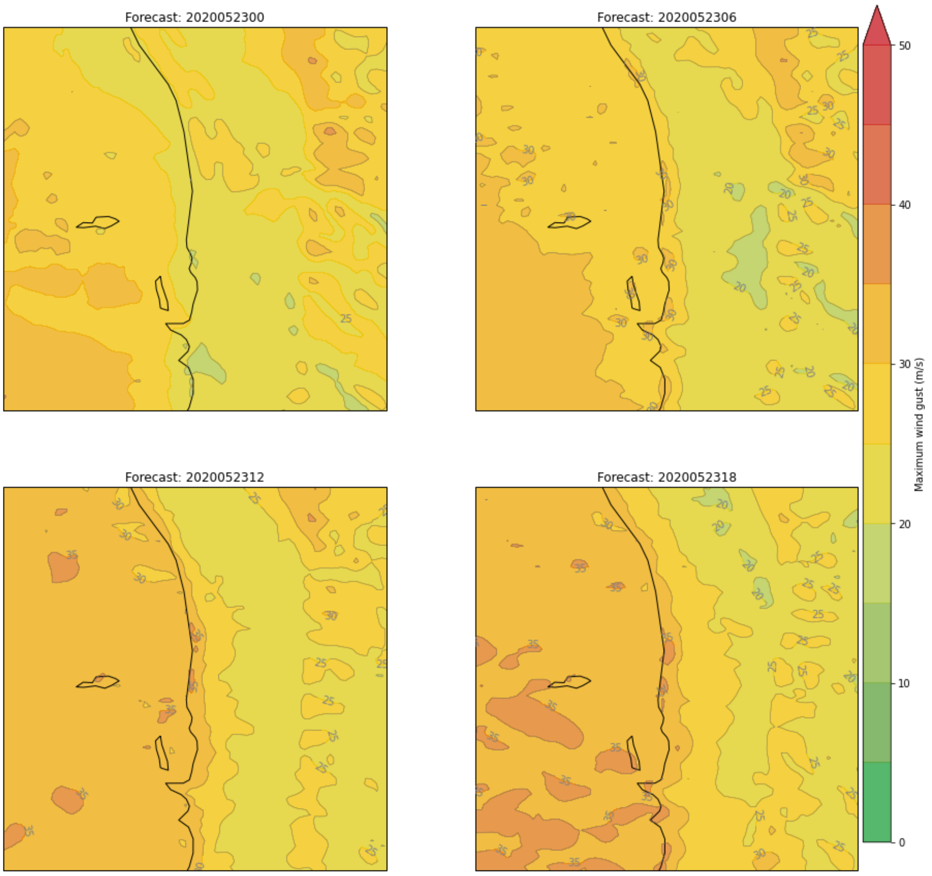

FIGURE 18: MAXIMUM 3-SECOND 10-M WIND GUST FORECASTS VALID AT 2100 UTC 24 MAY 2020 FOR FOUR ACCESS-PH SIMULATIONS INITIALISED AT 0000 UTC 23 MAY 2020 (TOP LEFT), 0600 UTC 23 MAY 2020 (TOP RIGHT), 1200 UTC 23 MAY 2020 (BOTTOM LEFT) AND 1800 UTC 23 MAY 2020 (BOTTOM RIGHT). IN THIS CASE, THE HIGHEST WIND SPEEDS ARE FORECAST TO AFFECT THE GREATER PERTH METRO AREA IN THE FORECAST WITH THE SHORTEST LEAD TIME (3 HOURS), COINCIDING WITH THE APPROACH OF THE MAIN STORM. MAXIMUM MODEL WIND GUSTS AT 2100 UTC ARE IN EXCESS OF 35 M S^{-1} (126 KM HR^{-1}).

Four successive ACCESS-City model forecasts were used to produce wind fields in the Greater Perth Region valid at the same time (2100 UTC on 24 May 2020; Fig. 18). The large and intense extratropical cyclone was producing measured wind gusts in excess of 110 km hr^{-1} around Perth, making it suitable for a wind impact assessment. The main result of this assessment is that the wind hazard prediction changes between a 21-hr forecast and a 3-hr forecast can translate to quantitative impact changes from negligible to moderate (Fig. 19). This sensitivity needs to be explored further in future studies and constitutes a second significant constraint on the potential usefulness of quantitative wind impact forecasts (in addition to the shortfalls of currently collected damage data for the derivation of vulnerability functions and verification of impact forecasts).

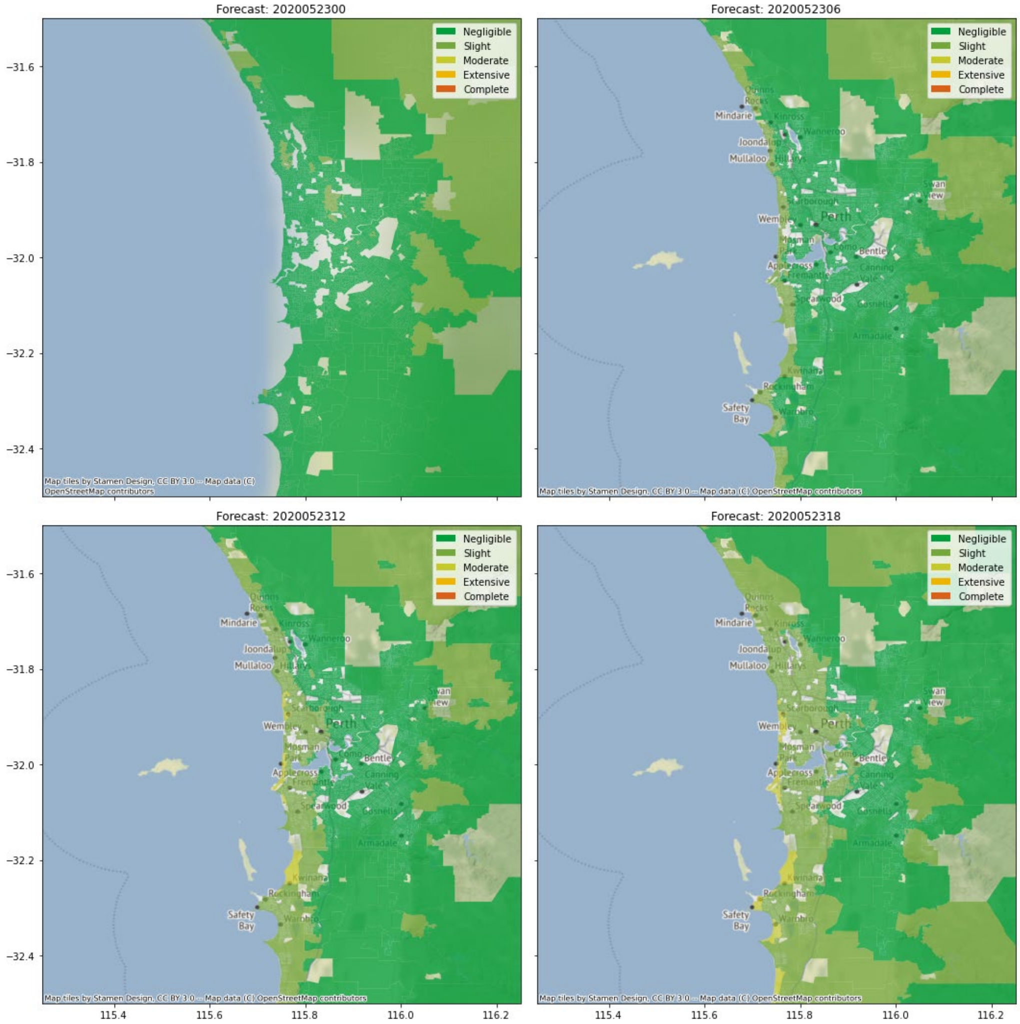

FIGURE 19: FORECAST MEAN DAMAGE STATE FOR SA1 GEOGRAPHIC AREAS AT 2100 UTC 23 MAY 2020 BASED ON THE FOUR SUCCESSIVE ACCESS-CITY MODEL INITIALISATION TIMES LISTED WITH FIG. 18.

SOME INTERNATIONAL PERSPECTIVES ON IMPACT FORECASTING

A poster presentation was delivered by Harald to the European Conference on Severe Storms (ECSS) showcasing the hazard prediction for a 2016 South Australian case using a more modern approach to interrogating output from high-resolution convection-permitting models such as the underlying model used to specify the wind hazard for the Dungog case. This 'storm attribute' approach is still relatively new in European countries and therefore attracted some interest. A key conversation with Elizabeth Webster from the South African Weather Service (SAWS) indicated that 'impact forecasts' at SAWS are not objectively derived model-based damage estimates, for example, but are hazard forecasts translated into qualitative and selected impacts by emergency managers on the ground. This approach means that emergency managers make the choices on which impacts deserve to be communicated, and which ones are left out.

At the UK Met Office a conversation with Joanne Robbins, head of the Weather Impacts Team, revealed that impact forecasting at the UKMO is also hampered by access problems to the required data, similar, or perhaps even more restrictive, to our own experience in Australia. The prime data access mechanism for Joanne's team is through the Natural Hazards Partnership, an association of government agencies, universities and other institutions.

Joanne also pointed out that impacts have multiple levels which can be seen as parts of the value chain. Physical impacts, such as blown-over trucks as predicted by the Vehicle Overturning Model (VOT) create further impacts down the value chain: extra costs to businesses, travel time increases etc. The Bureau's intention to impact-based forecasting, for example, therefore faces the additional task of needing to specify how many, and which, layers of impact (or which "segment" of the value chain) are within scope of its future service.

Finally, the UKMO launched one concerted effort to quantify wind impacts about 6 years ago, but the work did not result in useable outcomes at the time. It puts into perspective that the goals of this project are regarded as difficult, even at the most advanced impact forecasting organisations such as the UKMO.

SECOND END-USER WORKSHOP ON 25 AND 27 AUGUST 2020

A second project end-user workshop was held over four hours, split across two days in August 2020. Most of the 18 end-user attendees were present for the full duration of the workshop, and they represented 9 separate agencies (FRNSW, EMA, QFES, DFES, NSW SES, VIC SES, SA SES, BoM and BNHCRC).
The project stimulated and partially guided the discussions on focal topics of wind impact forecast verification (presentation by David Wilke), the sensitivity of impact forecasts to hazard model forecast lead times (presentation by Craig Arthur) and the desirability of supporting information and delivery mechanisms for hazard impact forecasts (led by Mark Dunford). There was abundant discussion amongst the attendees that went beyond the guiding topics above.
The short list of pertinent messages and feedback is listed here:

- The current format of the available Rapid Damage Assessment data (e.g., from the EICU) requires sophisticated and labour-intensive damage data pre-processing before these observations can be used for the verification of quantitative impact models
- A key tension is the desire of emergency response agencies to have available the total impact across all hazards (wind, rain, flood, coastal erosion etc.) and all impacted assets (residential housing, critical infrastructure, etc.), while quantitative impact modelling is already challenged when estimating the impact of a single hazard for a single asset.

- The project showed that, for the 2015 Dungog East Coast Low event, wind impact forecasts performed better than a simple 3-catgory wind-only forecast in the estimation of wind damage on residential properties
- A significant step forward for quantitative impact modelling would be the collection of damage assessment data that establish a link between the reported damage and the hazard(s) that caused it, and a classification of the damage magnitude. Matthew Hayne (BNHCRC) aptly commented that “any extension of research funding needs a program dedicated to data collection otherwise we would be spinning wheels.”
- Quantitative wind impact forecasts are very sensitive to fluctuations in wind hazard forecasts. Such fluctuations commonly occur in a subset of complicated weather patterns with low predictability (e.g., a tropical cyclone undergoing a transition into an extratropical system).
- Broadly, impact information is useful when presented at the granularity of Statistical Areas Level 1
- Both, 3-level and 5-level damage categorisation schemes would be useful to emergency response agencies to support community messaging, internal response, recovery and preparedness activities.
- Future impact forecast outputs should be ingested into GIS-based awareness/analysis platforms, but also be available as web pages and for direct download.
- A strong preference was expressed for access to human experts in the operations centres, due to the need for interactive exchange of information. ‘Static’ user guides or forecast outputs remain important, but are best delivered through a human expert who is equipped to interpret such outputs and can deal with variations in the presented scenarios.

SUMMARY

This project set out to pilot a multi-day spatial rain & wind impact forecast capability applicable to residential buildings, with the hazard components being predicted by high-resolution (convection-allowing) numerical models. Damage assessment data for the 20-22 April 2015 Dungog NSW east coast low event were sourced and its relationship to the wind strength and rainfall rate explored.
We found that the available damage assessment data were lacking some critical information needed to establish data-driven vulnerability relationships applicable to residential houses with respect to wind and rain. The reported damage needs to be categorised and linked to the hazard or hazards that caused it. The observed damage was often due to more than one hazard, raising the prospects that vulnerability relations might have to be crafted based on multiple interacting hazards.

As part of an extensive literature review into impact modelling undertaken by this project it has become clear that the literature on multi-hazard impact modelling is sparse, in particular on mature hazard impact models that aim to quantify hazards, exposure and vulnerability to produce quantitative physical impacts.

In regard to the available exposure data, areas where local building attributes need to be derived from housing attributes surveyed in other locations (e.g., Dungog NSW using survey data from Newcastle and Alexandria) significant errors in the exposure data are present at the town scale. Currently this does not allow meaningful impact estimates at town scales or smaller.

Due to our inability to derive new vulnerability functions from the available damage assessment data, the project needed to employ existing heuristic vulnerability relations that have been used by Geoscience Australia for scenario impact assessments for emergency management planning purposes.

There is a range of open questions that this project did not address. For example, a major factor in wind-related residential building damage is tree fall. A comprehensive wind impact model needs to include this impact pathway, which would require a range of additional datasets on tree heights, density, species, rooting depths, soil type, and many more. The effort required to stand up a tree fall model warrants a separate study. A second example is the sensitivity of the wind impact output to the initial accuracy of the input data (hazard, exposure, vulnerability). The maturity of the workflow developed in this project does not lend itself *yet* for such sensitivity studies as more testing would be required to ascertain the accuracy and comprehensiveness of the processes captured by our initial model. We have, at this point, merely created the platform from which to launch this required future work. Such work would additionally require that our recommendations for damage datasets be implemented to allow for a more reliable verification approach.

Primarily through conducting two end-user workshops in 2019 and 2020, the project has also revealed that there is a strong appetite for forecast impact products from end-users such emergency management agencies and Bureau operational meteorologists. Of interest in this context is our findings that impact forecasts, when verified against the existing damage assessment data, can outperform hazard-only forecasts, traditionally issued by the Bureau of Meteorology. Such verification efforts, however, required a significant amount of careful subjective assessment data filtering to ensure that any damage report used in the verification is the result of the specific hazard used in the impact simulation.

National Hydro-Meteorological Centres (NHMCs) around the globe have stated that impact (rather than hazard) forecasts are a major new strategic direction, so that our prototype study is well placed to meet an emerging vast need for ways to transition from hazard to impact forecasts. We have shown that it can be accomplished across more than one federal agency, that it can verify better than a hazard-only forecasts, and what changes to damage data collection is required to enable us to advance quantitative impact forecasting to the next level.

UTILISATION, IMPACT AND POTENTIAL NEXT STEPS

SUMMARY

We have produced a pilot of a quantitative wind impact prediction workflow, including assessment of its value using a 2015 East Coast Low severe weather event.

OUTPUT TITLE

Output description

The workflow integrates 0-2 day wind hazard forecast from the Bureau's ACCESS-City models with Exposure information from NEXIS and heuristic vulnerability function from Geoscience Australia to produce quantitative wind impact forecasts for residential buildings.

Extent of use

- As a pilot the product is not yet in use. Based on end-user feedback, the quantitative impact forecasts will be useful for the Bureau of Meteorology under its Future Warning Framework, and to emergency response agencies.

Utilisation potential

- Geosciecne Australia has submitted a proposal to automate the workflow set up in this project, using ACCESS-C3 wind gust data as the hazard driver. This is the logical next step towards end-user utilisation and adoption.

OTHER OPPORTUNITIES

The utilisation proposal crafted by this project originally intended to create threat polygons for predicted severe thunderstorms and the creation of attendant exposure reports. Over time, the proposal has changed in its aim and scope (as stated above). Future utilisation, however, should return to the original proposal as an easy-to-reach application of understanding and systems created or improved through the project.

Opportunities also continue to exist through the projects strengthening connections to the Weather Impact Team at the UK Met Office led by Joanne Robbins, and a building relationship with the World Meteorological Organisation (WMO) *Human Impacts, Vulnerability and Risks* task team chaired by Brian Mills from the University of Waterloo / Environment & Climate Change Canada. Through both relationships this project has forged connection with world-leading scientists who work on impacts of meteorological hazards, and thus have the potential to play a role in the quality assurance of future meteorological hazard impact prediction work in Australia.

PUBLICATIONS LIST

JOURNAL PUBLICATIONS

1 Schroeter, S., H. Richter, C. Arthur, D. Wilke, M. Dunford, M. Wehner, and E. Ebert: Forecasting the impacts of severe weather: A review. Submitted to the Australian Journal of Emergency Management (AJEM) on 4 September 2020.

2 Allen, J. T., E. R. Allen, H. Richter and C. Lepore, 2020: Australian tornadoes in 2013: Implications for climatology and the warning process. Mon. Wea. Rev., (submitted Aug 2020).

3 Hartigan, J., R. A. Warren. J. S. Soderholm and H. Richter, 2020: Simulated changes in storm morphology associated with a sea-breeze air mass. Mon. Wea. Rev., (accepted 3 September 2020).

4 Harald Richter, Craig Arthur, Serena Schroeter, Martin Wehner, Jane Sexton, Beth Ebert, Mark Dunford, Jeff Kepert, Shoni Maguire, Russel Hay, Mark Edwards: Impact Based Forecasting for the Coastal Zone. AFAC 2019, Extended Abstract.

CONFERENCE PROCEEDINGS – PAPERS

1 Richter, H, C. Arthur, S. Schroeter, M. Wehner, J. Sexton, E. Ebert, M. Dunford, J. Kepert, S. Maguire, R. Hay, and M. Edwards, 2018: Impact-based forecasting for the coastal zone. *Proceedings of the research forum at the Bushfire and Natural Hazards CRC & AFAC conference*, Perth, Western Australia. September 2018.

INVITED CONFERENCE PRESENTATIONS

1 Richter, H, C. Arthur, S. Schroeter, M. Wehner, J. Sexton, E. Ebert, M. Dunford, J. Kepert, S. Maguire, R. Hay, and M. Edwards, 2018: *Impact forecasting*. Invited presentation at BNHCRC NT Emergency Services Workshop in Darwin, October 2017.

2 Richter, H, C. Arthur, S. Schroeter, M. Wehner, J. Sexton, E. Ebert, M. Dunford, J. Kepert, S. Maguire, R. Hay, and M. Edwards, 2018: *Impact-based forecasting for the coastal zone: East coast lows*. Invited "ignite talk" at the Engineering for Climate Extremes Partnership (ECEP) workshop, Sydney, February 2018.

3 Richter, H.: *Severe local windstorms – a meteorologist's perspective*. Invited keynote presentation at the 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, 4-6 April 2018.

4 Richter, H, C. Arthur, S. Schroeter, M. Wehner, J. Sexton, E. Ebert, M. Dunford, J. Kepert, S. Maguire, R. Hay, and M. Edwards, 2018: *Impact-based forecasting for the coastal zone: East coast lows*. Invited presentation at the RFSA triennial conference, Sydney, July 2018.

INTERNATIONAL CONFERENCES

1 Richter, 1 H., and D. Sgarbossa: Use of convection-allowing model ensembles in forecasting severe convective hazards in Australia. European Conference on Severe Storms 2019, Krakow, Poland.

2 Richter, H., G. Collecutt, and A. Treloar, 2018: New developments in the Bureau's thunderstorm prediction system – Calibrated Thunder. Annual Assembly of the European Geophysical Union (EGU), Vienna, Austria.

RESEARCH ADVISORY FORUMS

1 Harald Richter, David Wilke, Beth Ebert, Craig Arthur, Martin Wehner, Shane Martin, Mark Dunford, Jane Sexton: Impact Forecasting for Severe Wind Events, Hobart RAF, Sep 2019.

2 Harald Richter, David Wilke, Beth Ebert, Craig Arthur, Martin Wehner, Shane Martin, Mark Dunford, Jane Sexton: Impact Forecasting for Severe Wind and Rain Events, Perth RAF, Jul 2019.

3 Harald Richter, David Wilke, Beth Ebert, Craig Arthur, Martin Wehner, Mark Dunford, Jane Sexton, 2018/2019: Impact forecasting for severe wind and rain events. Oral presentation at the Extreme Weather RAF in 2018/2019.

AUSTRALIAN METEOROLOGICAL AND OCEANOGRAPHIC SOCIETY (AMOS) ANNUAL CONFERENCES

1 Richter, H., C. Arthur, D. Wilke, S. Martin, M. Wehner, E. Ebert, M. Dunford, 2020: Validation of a prototype wind hazard impact model – the April 2015 Dungog case. AMOS Annual Conference 2020, Fremantle.

2 Richter, H.: Operational calibrated thunder probabilities, 2020: Are we getting better? AMOS Annual Conference 2020, Fremantle.

3 Allen, J. T., Edwina R. Allen, Harald Richter: Australian Tornadoes: Unpredictable or an evident hazard? AMOS Annual Conference 2020, Fremantle.

4 Richter, H., Craig Arthur, Serena Schroeter, Martin Wehner, Beth Ebert, Mark Dunford, Jeff Kepert, Shoni Maguire, Russel Hay, Jane Sexton, and Mark Edwards: Spatial impact forecasting for larger-scale wind and rain events along Australia's east coast. AMOS Annual Conference 2019, Darwin.

5 Richter, H, C. Arthur, S. Schroeter, M. Wehner, J. Sexton, E. Ebert, M. Dunford, J. Kepert, S. Maguire, R. Hay, and M. Edwards, 2018: *Impact-based forecasting for the coastal zone: East coast lows.* AMOS Conference, Sydney, February 2018.

6 Soderholm, J., H. McGowan, M. Mason, A. Dowdy, T. Wedd, A. Protat, and H. Richter, 2018: *South East Queensland hazard analysis and verification testbed – operations and preliminary results.* AMOS Conference, Sydney, February 2018.

7 Turner, K., J. Soderholm, T. Wedd, J. Callaghan, D. Grant, and H. Richter, 2018: *High-impact severe thunderstorm events in southeast Queensland.* AMOS Conference, Sydney, February 2018.

8 Walsh, K., C. J. White, K. McInnes, J. Holmes, S. Schuster, H. Richter, J. P. Evans, A. Di Luca, and R. A. Warren, 2018: *Natural hazards in Australia and east coast lows.* AMOS Conference, Sydney, February 2018.

9 Richter, H., G. Collecutt, and A. Treloar, 2018: *New developments in the Bureau's thunderstorm prediction system – Calibrated Thunder.* AMOS Conference, Sydney, February 2018.

10 Allen, J. T., E. R. Allen, and H. Richter, 2018: Australian tornadoes in 2013: *Implications for climatology and the warning process.* AMOS Conference, Sydney, February 2018.

AFAC/BNHCRC CONFERENCES

1 Richter, H., E. Ebert, J. Kepert, R. Stringer, C. Arthur, M. Wehner, C. Krause, M. Dunford, M. Edwards, J. Sexton, and R. Hay, 2017: *Impact forecasting – what does the forecast mean?* AFAC Annual Conference, Sydney, September 2017.

2 Richter, H, C. Arthur, S. Schroeter, M. Wehner, J. Sexton, E. Ebert, M. Dunford, J. Kepert, S. Maguire, R. Hay, and M. Edwards, 2018: *Impact-based forecasting for the coastal zone*. Invited presentation for the BNHCRC & AFAC Conference, Perth, September 2018.

3 Richter, H., Craig Arthur, Martin Wehner, David Wilke, Mark Dunford, Beth Ebert, 2018: The physical impact of strong winds and heavy rain on residential housing - a pilot study. Extended abstract (peer-reviewed). AFAC, August 2019.

4 Richter, H., C. Arthur, S. Schroeter, M. Wehner, E. Ebert, M. Dunford, J. Kepert, D. Wilke, S. Maguire, R. Hay, J. Sexton and M. Edwards: IMPACT-BASED FORECASTING IN THE COASTAL ZONE: THE USE OF EMERGENCY MANAGEMENT DATA IN THE VALIDATION OF SPATIAL WIND IMPACT FORECASTS. AFAC Conference 2019, Melbourne.

5 Richter, H., Craig Arthur, David Wilke, Beth Ebert, Mark Dunford, Martin Wehner, Jane Sexton, Shoni Maguire, Jeff Kepert, Russel Hay, Mark Edwards : IMPACT–BASED FORECASTING IN THE COASTAL ZONE: EAST COAST LOWS. Poster presentation at AFAC19.

6 Richter, H., Craig Arthur, David Wilke, Beth Ebert, Mark Dunford, Martin Wehner, Jane Sexton, Shoni Maguire, Jeff Kepert, Russel Hay, Mark Edwards: IMPACT –BASED FORECASTING IN THE COASTAL ZONE: EAST COAST LOWS – THE USE OF EMERGENCY MANAGEMENT DATA IN THE VALIDATION OF SPATIAL WIND IMPACT FORECASTS. Oral presentation at the Research Forum of AFAC19.

7 Richter, H., Craig Arthur, David Wilke, Beth Ebert, Mark Dunford, Martin Wehner: *An improved understanding of the built environment can improve forecasts of wind impact on residential buildings.* Poster presentation in lieu of the 2020 AFAC Conference.

BUREAU ANNUAL MODELLING WORKSHOP, NOVEMBER 2018

1 Richter, H., G. Collecutt, and A. Treloar, 2018: *New developments in the Bureau's thunderstorm prediction system – Calibrated Thunder.*

BUREAU OF METEOROLOGY SEMINARS

1 Richter, H.: NOAA's Hazardous Weather Testbed: The Spring Forecasting Experiment 2019. Seminar presented 21 August 2019.

2 The use of convection-allowing model in constructing today's severe thunderstorm story: Science Conversations. Short talk presented 11 September 2020.

ASWA ANNUAL CONFERENCE

1 Harald Richter: Convective Forecasting in the age of the convection-allowing model (CAM). Invited talk presented at the annual conference of the Australian Severe Weather Association.

TEAM MEMBERS

The team members listed below each had a different degree of project involvement. Substantial technical contribution came from Craig Arthur, David Wilke, Serena Schroeter and Claire Krause. The project members that "lasted the distance" are Craig Arthur, Harald Richter, Mark Dunford, Martin Wehner, and Beth Ebert. This endurance was partly driven by the circumstances allowing a 3-year commitment.

RESEARCH TEAM

Harald Richter (Bureau): Project leader. Severe convective weather, thunderstorms and its hazards (hail, wind, tornado, heavy rain), convection-allowing modelling of severe convective weather.

Craig Arthur (GA): Project co-leader. Tropical cyclone hazards, impact modelling

Serena Schroeter (Bureau; Years 1 and 2): Coupled climate modelling, Antarctic sea ice, physical oceanography, climate interactions, severe weather.

David Wilke (Bureau; Years 2 and 3): Operational weather forecaster and project researcher

Claire Krause (GA); Year 1

Shane Martin (GA): Hazard Support (Years 2 and 3)

Martin Wehner (GA): Vulnerability and exposure

Jane Sexton: Hazard (Years 1 and 2)

Carla Mooney (Bureau): Social science perspective on physical hazard impacts (Years 2 and 3)

Beth Ebert (Bureau): Verification, ensemble prediction

Mark Dunford (GA): NEXIS

Jeff Kepert (Bureau): Tropical cyclones, atmospheric dynamics, fire weather, turbulence. (Year 1 only)

Shoni Maguire (Bureau): Warning policy (Year 2 only)

Russell Hay (GA): Exposure Lead (Years 1 and 2)

Mark Edwards (GA): Vulnerability lead (Years 1 and 2)

END-USERS

The project end-user community shifted somewhat over time as participants changed roles and were replaced by new arrivals. The project is particularly grateful for the consistently outstanding engagement by Steve Gray (DFES), Anthony Day (NSW SES) and Roger Mentha (FRNSW).

End-user organisation	End-user representative	Extent of engagement (Describe type of engagement)
Bureau of Meteorology	Steven Hadley (QLD)	
Bureau of Meteorology	David Grant (QLD)	
Bureau of Meteorology	Simon Louis (TAS)	End-user statement
Bureau of Meteorology	Jane Golding (NSW)	
Bureau of Meteorology	Paul Bierman (SA)	
Bureau of Meteorology	Dean Sgarbossa (VIC)	
DFES	Steve Gray	Frequent Contributions. Hosted first project end-user workshop in 2019.
QFES	Oliver Smith	Succeed John Rolfe
QFES	John Rolfe	
QFES	Peter Readman	
NSW SES	Tony Day	Instrumental in BEACON data acquisition; frequent feedback
NSW SES	Dianne Gordon	Succeeding Tony Day
NSW SES	Allison Flaxman	Succeeding Tony Day
SA SES	Graeme Wynwood	
SA CFS	Andrew Stark	Strong communication
VIC SES	Tamsin Achilles	
FRNSW	Steven Hayes	
FRNSW	Roger Mentha	Lead end-user – regular project interaction
SA DEWNR	James Guy	
AGCCC	Joe Buffone	
AGCCC	Brian Foo	Strong communication

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14 Perry M., 2017: Understanding Weather and Climate Risk. What is risk in a weather and climate context? https://www.geolsoc.org.uk/~/media/shared/documents/Events/Past%20Meeting%20Resources/Sharing%20an%20Uncertain%20World/Perry%20Matthew.pdf.

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APPENDIX A: SUMMARY OF DELIVERED MILESTONES

Code	Item	Comments
Year 1		
1.1.1	End-user panel is established and priorities agreed on exposure assets, impacts considered, and visualisation outputs to be produced	Assets: Agreement to focus on residential property (and possibly power distribution assets down the track) Hazards: Focus on damaging winds ; rain ingress down the track if damage data permits this Visualisation outputs: more appropriate to develop the detailed outputs in collaboration with end-users as results are produced
1.1.2	Detailed project plan completed and agreed between parties	Final allocation of individual researchers against milestones on 12 December 2017
1.1.3	Poster for BNHCRC Conference completed	Was showcased at the Showcase in Adelaide in July 2017
1.1.4	Glossary of project terminology developed	Circulated to end-users 22 September, to be finalised in October.
1.1.5	Quarterly Report	
1.2.1	Review of international impact forecasting approaches completed (CM 2.2.12)	A draft was completed in May 2018 and is currently being circulated within the project team for comment. Some additional impact-related studies not currently contained in the draft will be added to it as part of this review. The next step after that is the approval process within GA / BoM. This process includes an additional internal review. Publication will take place through a peer-reviewed journal and through the BNHCRC website (for easier access by the emergency management community and other end-users).
1.2.2	Collection of 20 April 2015 datasets	The project requires damage assessment survey data to relate building damage to the magnitude of the underlying hazard(s). Two such datasets were sourced by the project: [1] NSW SES BEACON data were sourced through one of the project's end-users, Tony Day. [2] The second damage assessment dataset, the Emergency Information Coordination Unit or EICU dataset, was provided by Fire and Rescue NSW.
1.2.3	Quarterly Report	
1.3.1	Split SES callout data for the 20 April 2015 event into new event-specific wind damage categories	At this point the project made an impactful discovery regarding the available damage assessment datasets. • Only the Emergency Information Coordination Unit (EICU) dataset contained any classification of the damage to buildings into categories, the BEACON data did not • Neither dataset consistently linked the documented damage to the hazard(s) that caused the damage The information gaps in the available damage datasets affect the project milestones 1.3.1, 1.3.2 and 1.4.1. It also put the project into a position of needing to adjust its deliverables to account for the nature of the damage assessment datasets.

		A new project deliverable was identified as a consequence. We approached the NSW SES with a request to include damage categories and hazard-damage link information into the BEACON damage assessment reporting template. Tony Day, after consultation with a BEACON developer, communicated that he supported this request and that the changes to implement it are relatively minor.
1.3.2	Split SES callout data for the 20 April 2015 event into rain damage categories.	As a work-around, the project decided on the following adaptations: • We will continue to construct the data workflow from ACCESS-C model output through to a spatial impact display using simple existing or *interim* fragility relationships for wind (Fig. 2 below) and rain • In parallel, we will develop more basic fragility relationships for the wind and rain hazards that will be based on multiple severe wind and rain weather events, not just the 20-22 April 2015 Dungog event. Multiple events will allow us to be more selective on which components of the damage assessment data we choose top use in the construction of fragility relationships without dealing with too small a sample size. In the meantime, we also seek to develop a more basic fragility curve, where we identify a threshold above which damage occurs. The probability of damage is based on a simple count of damaged buildings in each region. Currently we have mapped damage onset to wind speed (see Figs. 3 and 4 below), but not yet to rainfall rate/accumulation.
1.3.3	Presentation/Poster for AMOS 2018 conference.	An oral presentation focusing on the current project findings and status was delivered by Harald Richter at AMOS 2018 in session 4.2B on Thursday 8 February 2018.
1.3.4	Quarterly Report	
1.4.1	Determine wind speed thresholds for each of the event wind damage categories	The damage assessment data available to the project thus far do not allow for an attribution of reported damage to a specific hazard (BEACON and EICU data – see previous quarterly report for acronyms). The BEACON data also don't categorise the damage by damage state or degree of damage. The project needed to find a workaround to address this milestone. Two more immediate pathways have been found: 1. To complete the construction of the end-to-end data workflow, from ACCESS model output to spatial impact, an interim generic fragility relationship will be used (see Fig. 2 in the Y1/Q3 report showing that relationship) A second option is the construction of a simplified fragility relationship that simply determines a single model wind speed threshold that separates no house damage from house damage. This approach can be applied in the absence of any degree of damage information. Again, the Y1/Q3 report shows the results of this exploration in Figs. 3 and 4.
1.4.2	Reformat ACCESS wind and rain outputs for compatibility with GA	A key software component on the project workflow is GA's "HazImp" code which ingests a hazard grid and produces impact output. The Bureau's ACCESS models produce

	systems	NetCDF output. Currently, the project has managed to manually convert the NetCDF output to GeoTiff format which is the native input format of HazImp. To automate this capability, we are considering the approach of modifying HazImp to directly ingest NetCDF output. This is work in progress. A second modification of HazImp, although not part of this milestone, is the addition of shapefile outputs to HazImp, so that the Bureau's primary operational data display system, Visual Weather or VW, can easily display the impact information.
1.4.3	Draft for a short article on impact forecasting approaches written	A near-final draft of the article on impact forecasting approaches has been circulated for review by the project team on 8 June 2018. We are expecting the manuscript to be ready for formal peer review in July 2018. Publication is intended through the BNHCRC website (easy access by stakeholders) and in the peer-reviewed literature (as a quality control assurance measure).
1.4.4	Quarterly Report	
Year 2		
2.1.1	Preliminary methodology for project-specific wind impact model developed using idealised wind vulnerability relations	The project developed an end-to-end impact forecast methodology several months ago. This workflow connects the Bureau's numerical weather prediction model hazard outputs to the spatial graphical impacts. The use of idealised, as opposed to damage data-derived, vulnerability relations has proven successful in moving the project forward.
2.1.2	Workflow for the above integrated wind impact model forecast tested and documented	The *HazImp* software on the National Computing Infrastructure (NCI) machine now runs end to end to produce spatial impact output in a vector shapefile format. This workflow is accompanied by an explanatory document.
2.1.3	Production of the first preliminary visualisation outputs from the fully integrated wind impact modelling pilot system using idealised wind vulnerability relations	Craig Arthur and Serena Schroeter collaborated during an intense sprint to finalise the production of a spatial impact product that could be visualised through Visual Weather in late September.
2.1.4	Short article on impact forecasting approaches submitted	Full-sized paper has been submitted to *Weather and Forecasting*. Note that the article is a full-sized review paper, not just a short article.
2.1.5	Poster for BNHCRC Conference	Poster has been presented at the AFAC conference in Perth during 5-7 September 2018.
2.1.6	Quarterly Report	
2.2.1	Initial validation methodology for the wind impact model developed	An initial impact forecast validation methodology using EICU damage assessment data has been devised. Early exploration of the available data for the Dungog case show that EICU data have only limited value in a spatial wind impact prediction given the underlying damage assessments focus on a few selected towns only. The project will trial SES callout density (number of callouts per area) next.

2.2.2	Identification of several larger-scale strong wind / heavy rain cases within the 1.5 km BARRA reanalysis domains with corresponding high-quality damage assessment data	Three suitable cases have been identified for which high quality EICU data and high resolution model-produced hazard data are available. ● April 2015: Hunter Valley east Coast Low ● Dec 2015: Widespread supercells (and one confirmed tornado) south and in Sydney ● June 2016: Strong East Coast Low near Sydney. For each case, high resolution BARRA (reanalysis) data and EICU damage assessment data have been secured. The next step is to derive wind-based and rain-based vulnerability relationships for residential housing across these three cases.
2.2.3	Quarterly Report	
2.3.1	Workflow for a preliminary rain impact model forecast tested and documented using idealised rainfall vulnerability relations.	A rain hazard workflow was replicated from the original wind impact workflow, with a range of rainfall hazard proxy forecasts from the Bureau BARRA-SY reanalysis produced for ingestion into the impact prediction code *HazImp*. The rain vulnerability relations used at this early stage are nominal functions that are presently no more than rescaled copies of the previously used wind vulnerabilities for residential buildings.
2.3.2	AMOS 2019 Conference Presentation / Poster.	The project has been awarded an oral presentation in Session 19 on Impacts and Risk Assessment for Weather Extremes. The reason for the milestone delivery deferral is the shift of the annual AMOS conference from its usual time slot (February) to 11-15 June 2019. A submission of a premature presentation in time for this report would imply that project results to be obtained over the next ~2 months would not be incorporated.
2.3.3	Quarterly Report	
2.4.1	Generate component or ingredient maps for wind and rain impact forecasts.	The 31 July 2019 end-user workshop in Perth (see 2.4.4) asked the project's end-users to manually combine the individual layers (hazard, exposure, vulnerability) to estimate the final impact. This was only done for a wind impact case, though. With a rain-based impact predictor determined by the QDA below (see 2.4.3) and, for now, vulnerability and exposure layers being the same as for wind impacts, the milestone is essentially delivered.
2.4.2	Define dual-hazard damage predictor from identified wind / rain cases.	This deliverable needs to draw on results from milestone 2.4.3. It will be the quantitative description of impact values beyond a chosen threshold as a function of optimised wind and rain predictors.
2.4.3	Demonstration of a wind and rain combined impact product.	A combined wind and rain impact product awaits the outcome from a Quadratic Discriminant Analysis (QDA) technique. The QDA allows for the determination of an optimal wind and rain hazard combination given a known spatial impact grid.
2.4.4	First end-user workshop in which the wind and rain impact forecasting systems	An end-user workshop with just under 20 attendees was held at DFES in Perth on 31 July 2019. The main goal was to collect feedback on the current project workflow and

	are tested	delivery of an impact product. A secondary goal was to define potential future activities with end-users under the research utilisation banner.
2.4.5	Quarterly Report	
3.1.1.	Update wind impact forecast system and visualisation outputs based on end-user workshop feedback	The 31 July 2019 end-user workshop in Perth (see milestone 2.4.4) contained a detailed discussion with a range of end-users of how the demonstrated wind impact forecast methodology, including its visualisation, ought to be augmented. However, there were no material suggestions for such alterations.
3.1.2.	Refined validation methodology developed and indicative results generated for the wind impact model	A very detailed and careful verification methodology has been developed based on the only viable damage dataset available to the project (20-22 April 2015, Hunter Valley). The verification report for the Dungog case is intended for later publication (not a milestone, but a worthy endeavor).
3.1.3.	Poster for BNHCRC/AFAC Conference	A short abstract, a 13-page paper and an oral presentation were produced for the 2019 AFAC conference. All of these focus on the current status and results to date of the project.
3.1.4.	Quarterly Report	
3.2.1.	Extend wind impact forecast pilot to allow multiple forecast lead times	The goal of "multiple lead times" is to ascertain how wind impact forecasts change as the model lead time decreases from ~1.5 days to only a few hours. ACCESS-City model forecasts (rather than the BARRA-SY reanalysis) will be used for this purpose.
3.2.2.	Draft for peer-reviewed journal article on the wind impact prediction system highlighting issues (and their solutions) with dual-hazard impact prediction system development.	A draft of a paper that reviews quantitative impact prediction systems across the globe exists, but was rejected for publication by Weather Climate and Society. The basis for the rejection was, above all, confusion by some reviewers whether the paper was a review paper or was meant to publish our own impact prediction system which, at the time of submission in late 2018, was only in its infancy. While the draft is complete, it will require substantial work before submission (milestone 3.3.3.)+
3.2.3.	Quarterly Report	
3.3.1.	Second End-User Workshop to test and appraise the updated wind impact forecasting system.	The workshop was help in two separate 2-hour sessions on 25 and 27 August 2020. A workshop report has been produced, including recommendations for future utilisation projects.
3.3.2.	AMOS Conference Presentation.	On oral presentation was delivered to a well-attended session in Fremantle on 10 February 2020.
3.3.3.	Peer-reviewed journal article submitted.	The paper has been submitted to the Australian Journal for Emergency Management (AJEM) on 4 September 2020.
3.3.4.	Quarterly Report, Annual Report and Self-Assessment matrix.	Annual report is this report. QR 3 has been delivered.

3.4.1.	Minor updates to the wind impact forecasting system and visualisation outputs are applied based on feedback from the second end-user workshop	The second end-user workshop report has compiled a section of extra metrics end-users expressed an interest in. A utilisation proposal by Geoscience Australia which aims to automate the wind impact workflow developed during this project will implement the suggested system extensions.
3.4.2.	Synthesis Report summarising all project activities.	The Synthesis Report is being submitted in tandem with the final quarterly report (item 3.4.3.)
3.4.3.	Quarterly Report	Delivered.