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IMPROVED PREDICTIONS OF SEVERE WEATHER TO REDUCE COMMUNITY IMPACT

Annual project report 2015-2016

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Cover: A thunderstorm looms over Sydney in April 2015.

Photo: cksydney, Flickr

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EXECUTIVE SUMMARY

We aim to study the dynamics, predictability and processes of severe weather, including fire weather. We seek also to improve forecasts of severe weather, and to better depict forecast uncertainty in these events, thereby facilitating better risk management and more cost-effective mitigation. Our research into ember transport in smoke plumes and the meteorology of the Blue Mountains bushfires of October 2013 has reached maturity, and journal articles have been written. We continue to develop our work on pyrocumulus clouds, and the east coast low event of April 2015, and have commenced a study of an eyewall replacement cycle in a tropical cyclone. These studies span a wide range of time and space scales and require a range of different methods.

Our ember transport work has confirmed that the mean travel distance of firebrands for a given fire intensity depends mainly on wind speed. However, the spread in the landing positions shifts from being substantially cross-wind at light winds, to dominantly along-wind at high winds. This spread is greatly increased by the turbulence in the plume, and the maximum spotting distance can be more than double the mean for this reason. These sophisticated and computationally intensive calculations can be used to inform the development of physically realistic and computationally cheap parameterizations of ember transport for use in fire models.

We have also used our plume modelling to study pyrocumulus clouds. Intense fire plumes in suitably moist environments can lead to cloud development, with the possibility of strong downbursts – one of our simulations is shown on the cover of this report. We have analyzed the processes that lead to pyrocumulus, with special attention on the relative importance of moisture from two sources, the atmosphere and combustion, and shown that the latter is close to negligible. We aim to use the knowledge gained to develop a forecast tool for pyrocumulus formation.

Although the Blue Mountains fires of October 2013 persisted for several weeks, much of the spread occurred on the 17th. While this was expected to be a day of high fire risk, the extreme fire spread was not anticipated and the causes were unknown. Our high resolution simulations showed that the downward extension of high upper-level winds to the vicinity of the fire ground, caused by mountain wave activity, was a factor. In addition, the marked wind change on that day was associated with a dry slot, but the underlying cause of that dry slot seems to be different to previously documented cases.

East coast lows are intense low-pressure systems that form over the sea adjacent to the east coast of Australia, most commonly along the New South Wales coast. We continue our analysis of the event of 20-23 April 2015, using, for the first time, an ensemble of 24 simulations rather than just a single forecast. Collectively, these simulations accurately predict the position and intensity of the low, the strong winds and the rainfall. The differences between them give insight as to the forecast uncertainty, the overall envelope of areas at some risk, and those at highest risk. The ensemble also enables insight into the processes that lead to the rapid intensification of these systems. The risk these systems pose was further illustrated by the two events in June of 2016.

END USER STATEMENT

Paul Fox-Hughes, *Tasmanian Regional Office, Bureau of Meteorology*

Severe weather events can affect large areas, but their most damaging aspects tend to be concentrated in relatively small regions, and the mechanisms that underlie this observation are not always obvious. For this reason, the high resolution numerical weather modelling that the High Impact Weather group have undertaken as part of the BNHCRC is vitally important for our understanding of the processes leading to severe weather, whether those be fire weather events such as the Blue Mountains State Mine fire which the team has studied and documented, severe thunderstorms, or the details of processes occurring during tropical cyclones.

The High Impact Weather group is also carrying out important work on ember transport, which is not well understood, and consequently poorly modelled (or not modelled at all) in current fire behaviour models, and is investigating the conditions under which pyrocumulonimbus events occur. The latter have developed in some of the worst fire events in recent Australian (and overseas) history, and can be very dangerous, aggravating what are often already very gusty, highly variable winds, and igniting new fires through lightning. Both of these phenomena relate to plume modelling, also being undertaken by the HIW group. Advances in understanding plume behaviour will have a number of benefits, including improved smoke transport modelling.

The group's work in ensemble modelling also has far-reaching implications. It is again vitally important that meteorologists and emergency managers gain an understanding of the potential of ensemble modelling, especially in severe weather events such as the Dungog storm, in order to quickly make the best use of ensembles when they are implemented operationally, as they will be very shortly. The group's work in this area has already demonstrated the substantial potential of ensemble modelling.

As an end user, I'm always very keen to see the results that the High Impact Weather group in the BNHCRC present, and impressed at the breadth and impact of their work.

INTRODUCTION

This project, within the monitoring and prediction cluster, uses high-resolution modelling and the full range of meteorological observations to better understand and predict important meteorological phenomena. We have studied phenomena including fire weather, east coast lows and tropical cyclones. Outcomes from the project will contribute to reducing the impact and cost of these hazards on people, infrastructure, the economy and the environment.

During this year, we have seen much of our research approach or reach maturity. In particular, we have prepared journal articles marking the completion of work on two topics. The first of these is the development of a simulation framework for studying the processes that influence long-range spotting in bushfire plumes, and the analysis of those results. This work lays the foundation for the development of a method for approximating this transport calculation that is computationally fast enough to be incorporated into fire spread models, work that we hope to undertake in the future.

The second completed activity has been our analysis of the meteorology of the Blue Mountains fires of October 2013, which focussed on the most severe day and fire of that event, the State Mine fire on October 17. We found two meteorological factors that likely contributed to the extreme conditions on that day, mountain waves and a dry slot of unusual origin.

We have made substantial progress on our case study of the April 2015 east coast low, which produced severe flooding, winds and coastal erosion on the north coast of NSW. This study is the first we have undertaken using ensemble modelling, and the results of this study, as well as helping to understand the dynamics of this event, will also help guide users to make better use of this coming data source in the future.

We have also made substantial progress on our work with pyrocumulus development. We have adapted the plume modelling framework to simulate pyrocumulus, and are exploring the relative roles of atmospheric and combustion-related moisture in the cloud formation. We have completed a survey of current understanding and forecast techniques, and will be working towards developing improved techniques in the coming year.

This report summarises our main activities this year, and presents some key results from the above studies. Please note that this report represents the current state of work that may still be in progress, and that some results may be updated as the research continues.

PROJECT BACKGROUND

The project uses high-resolution modelling, together with the full range of meteorological data, to better understand and predict several important meteorological natural hazards, including fire weather, tropical cyclones, severe thunderstorms and east coast lows. The outcomes from the project will contribute to reducing the impact and cost of these hazards on people, infrastructure, the economy and the environment. Specific outcomes will include:

- Improved scientific understanding of severe weather phenomena relevant to Australia.
- Improved knowledge of how to best predict these phenomena, including model configuration and interpretation.
- Contribute to the post-event analysis and "lessons learned" of selected severe events that occur during the course of the project.
- Inform the development of numerical weather prediction (NWP) systems specifically for severe weather.
- Communicate the above knowledge through seminars, conferences and publication in the peer-reviewed literature, to the scientific and operational communities.

Extreme weather often occurs at relatively small scales – here, the devil really is in the detail. For example, the intense extra-tropical cyclone of June 2007 that grounded the Pasha Bulker coal carrier 20 metres off Nobbys Beach (Newcastle) and resulted in nine deaths had only a narrow belt of intense winds and rainfall. Even when the meteorology driving the event is not small scale, small-scale perturbations within the overall framework can have a significant effect, as we have seen in the fine-scale meteorology we simulated for Black Saturday and other severe fire events. Accurate forecasts and understanding of such small-scale processes requires high-resolution modelling. Developing and validating such modelling, and extending it to all hazards, is the first aim of this project.

Forecasts are never perfect, but they are nevertheless useful. Forecasts are especially useful in severe weather events, since they play an essential role in allowing communities, industry and emergency services to prepare and mitigate the impacts. Forecasting therefore underpins the work of emergency services and related agencies, and makes the PPRR (Prevention, Preparedness, Response and Recovery) process more efficient and effective. Because forecasts are inherently uncertain in the severity, location and duration of an event, preparation needs to be more widespread than the eventual impact – but this over-preparation comes at a cost. Detailed prediction of the probabilities of severe impacts would avoid the risk of failing to alert areas with the chance of an impact, while minimising the cost of over-warning. Thus the second aim of this project is, for a small number of selected events, to provide pilot predictions of not just the most likely course of events, but also the level of uncertainty, by identifying plausible alternative scenarios and their likelihoods. For example, Tropical Cyclone *George* made landfall near Port Hedland in 2006 after making a sudden turn towards the coast, resulting in three deaths. The deterministic predictions did not capture this direction change, but the probabilistic systems indicated that such a change, while unlikely, was possible.

A key aim of this project is to develop scientific understanding and to assist with the "lessons learned" from severe events. For example, the Beechworth-Mudgegonga fire on Black Saturday dramatically increased in activity around midnight, while the Margaret River fire of 2011 re-intensified overnight and broke control lines early the next morning. Each of these examples opposed the expected diurnal trend in fire behaviour, but our high-resolution modelling studies has identified small-scale meteorological phenomena that explain the unexpected behaviour. Our research thus adds to the collective wisdom of fire-fighters and weather forecasters, improving our ability to manage these events and reducing the risk of adverse outcomes in the future.

The principal numerical weather prediction NWP modelling system used in this project is ACCESS, the Australian Community Climate and Earth-System Simulator. ACCESS is based on the UK Met Office's NWP system and is used operationally within the Bureau of Meteorology and by several other overseas national weather services. It therefore benefits from a wide user base, and the discipline of operational use and continual verification. It is presently the second-best performing operational NWP system in the world. The only system to consistently outperform it for global prediction is a global-only model which cannot be run in the high-resolution limited-area mode necessary to simulate fine-scale meteorology.

For situations where extremely high resolution modelling with a grid spacing of tens of metres, and the capacity to explicitly resolve atmospheric turbulence is needed, we also use the UK Met Office's Large-Eddy Model (LEM). This specialised model is designed not for forecasting, but rather for understanding phenomena that are highly sensitive to turbulence, including boundary layers, fire plumes and convective clouds.

WHAT THE PROJECT HAS BEEN UP TO

EMBER TRANSPORT

Our main activity in the ember transport component of the project has been further analysis of the data reported in the last annual report, and preparation of a journal paper for the *International Journal of Wildland Fire*.

To recap, in the last report we described how we simulated a turbulent plume within a realistic atmospheric boundary layer using a large eddy model (LEM), which explicitly simulates much of the atmospheric and plume turbulence. The LEM uses a very fine grid spacing of just 50 m, as compared to several, to several, tens of kilometres for typical numerical weather prediction systems. We then took the 3-dimensional winds output from this high-resolution plume simulation and used them to simulate the transport of embers, calculating the trajectory and landing position of a sufficiently large number of embers to generate a statistically significant picture of the landing distribution.

Since the last report, we have produced simulations for a wide range of wind speeds and ember fall speeds. It is important to consider a range of fall speeds, since different types of embers have different densities and aerodynamic properties. Figure 1 shows the distribution of landing position for a range of wind speeds, and demonstrates that the landing positions are widely spread, both laterally and along the wind direction. As the wind speed increases, the along-wind spread and mean distance increase, but the lateral spread decreases.

This substantial spread is due to turbulence within the plume. Similar calculations with the time-average of the plume, which removes the turbulence, show substantially less spread, but little difference in the mean transport distance. Figure 2 shows cross-sections of the updraft within plumes at two wind speeds, along with instantaneous ember distributions. The upper panels show an instantaneous snapshot, while the middle panels show the time-mean updraft. Note the high degree of variation in the updrafts in the snapshot, compared to the mean. The plot of the updraft also includes a measure of the average turbulence level (contours), showing that the strongest fluctuations are concentrated on the upwind side of the plume.

The lowest panel in Figure 2 shows a snapshot of ember transport within the two plumes. The effect of turbulence on the ember transport is especially marked at high winds, for embers in a momentarily weak part of the plume fall out, and once they have departed the plume, continue to descend in the clear air below. The patchiness of the updraft leads to embers being deposited in distinct clumps, and an observer on the ground would see episodic patches of ember fallout. A proportion of embers happen to reside in mainly strong parts of the plume as they are carried along, and these are transported over twice as far as would be expected if the turbulence was neglected.

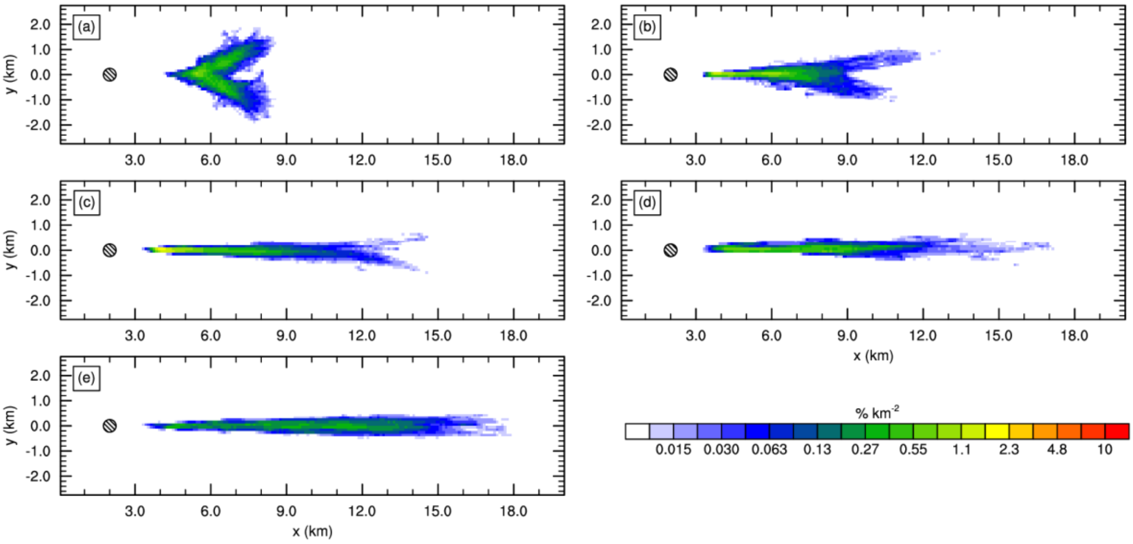

Fig. 1: Ember landing position at wind speeds of (a) 18, (b) 27, (c) 36, (d) 45 and (e) 54 km/hr. The contours are logarithmically spaced, and represent the relative density of embers landing at that location. The fire is indicated by the circle to the left of the plots.

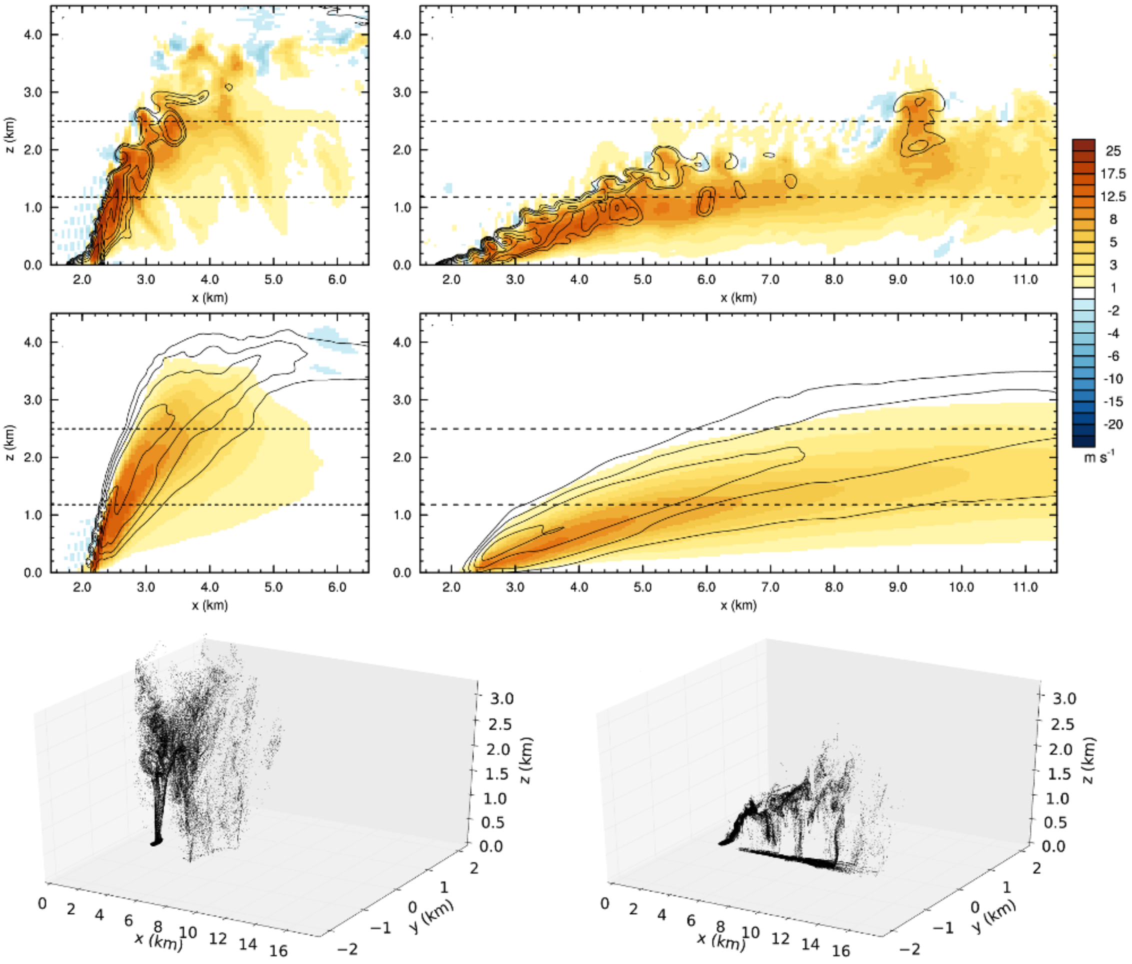

Fig. 2: Ember transport in background winds of 18 km/hr (left) and 54 km/hr (right). The top row shows a snapshot of the updraft in the fire plume, while the middle row shows the time-average updraft (shading) and intensity of the turbulent fluctuations (contours). The lowest row shows a snapshot of embers within the plume, including those that have fallen from the plume and are either continuing to descend, or have already hit the surface.

BLUE MOUNTAINS FIRES

The Blue Mountains bushfires of October 2013 were a major event, with over 200 houses damaged and an estimated area of 165 054 ha burnt. The worst day was 17 October, when the State Mine fire grew from 1036 ha at 11:56 am to 12 436 ha by 9:46 pm, an increase in area of over 11 000 ha in about 11 hours.

We prepared high-resolution numerical weather prediction simulations for the three most severe days in the period of the fires (namely, the 13th, 17th and 23rd of October), but after further examination focussed our analysis on conditions on the 17th. These simulations were prepared using the ACCESS system, as used for operational prediction by the Australian Bureau of Meteorology, but at substantially higher resolution. In particular, we performed a series of model runs nested to progressively higher resolution, with the highest resolution being a grid spacing of 440 m. These simulations were validated against the available surface and upper air observations.

Examination of weather data in the vicinity of the fire showed that the temperature was above average for the time of year, but not exceptionally so and well below typical summertime extremes. There was, however, a period of unusually strong winds and a very marked reduction in humidity, both of which approximately coincided with the major fire run. Our subsequent analysis focussed on determining the meteorological processes that caused these factors.

The simulation revealed a deep and strong region of mountain waves over the ‘Blue Mountains during the day on the 17th. Figure 3 shows a plan view of vertical motion at 4.5 km height at 1 pm local time across the area, in which blue corresponds to descent and red to ascent. The simulation also reveals, at the same time, a downward extension of the strong winds aloft in the vicinity of the fire (Fig. 4) collocated with the mountain waves excited by the flow over the Great Dividing Range. We conclude that this process probably caused the strong winds observed over the fire ground. Mountain waves are common in the atmosphere, and have previously been identified as a factor in Australian bushfires such as Margaret River (Kepert and Fawcett 2013) and Aberfeldy (Wells et al. 2014), as well as overseas (Coen and Schroeder 2015). The Blue Mountains case is unusual in the Australian context in that this is the first case we know of where the mountain waves that contributed to the extreme fire behaviour occurred during the day.

The marked drying observed over the fire is shown by the model simulation to have propagated in from the southwest, in association with a wind change (Fig 5). In contrast to the mountain waves, which are locked to the location of the Great Dividing Range, the dry slot is a larger-scale feature that narrowed and sharpened as it approached the fire. In recent years, dry slots have been identified as a contributing factor in several serious Australian fires, and a considerable body of work has investigated the processes involved (Mills 2005, 2008). In Mills’ work, the dry slot is described as forming as a result of descending air in the transverse circulation across a front, which brings drier high-altitude air to the top of the atmospheric boundary layer. Vertical mixing within the boundary layer then transfers the dryness to the surface. However, careful examination of the Blue Mountains simulations showed no evidence of this process, and nor did examination of the satellite imagery reveal a dry slot similar to that seen in the earlier studies. Rather, it seems that the feature in this case was the result of dry continental air being squeezed between two moist air masses, with very little vertical motion. This finding is important, for it alerts forecasters and fire managers to be aware that the known dangers of a dry slot can occur in more than one way.

The research phase of this component of the project is now complete, and we have prepared a journal paper describing the results for the international journal *Monthly Weather Review*.

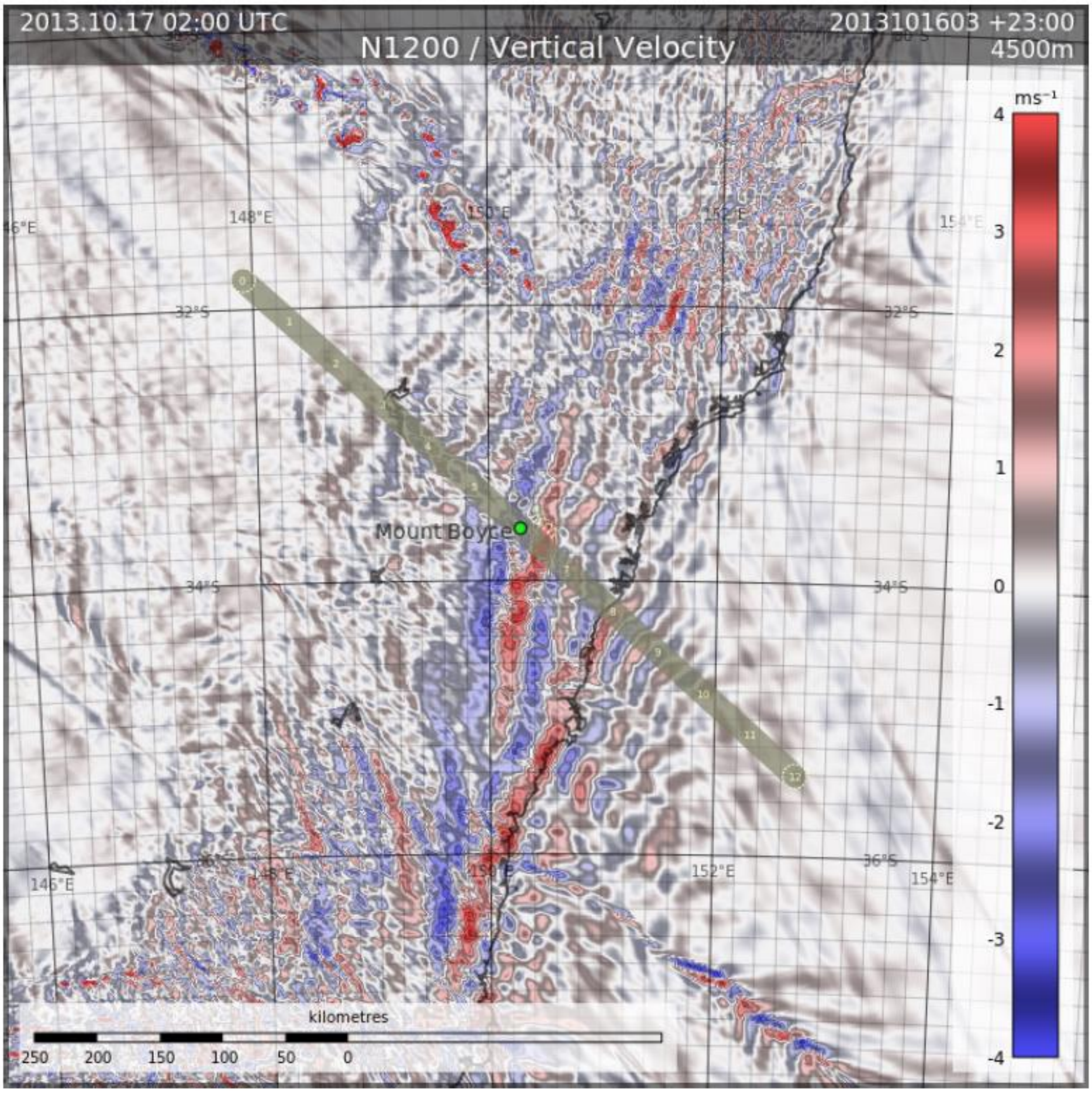

Fig. 3: Simulated vertical motion 4.5 km above mean sea level at 1 pm (local time) 17 Oct 2013. Blue air is descending, and red ascending. The linear bands of ascent and descent are the signature of mountain waves. Although the topography is mostly below 1 km in height, the mountain waves extend to and above this level.

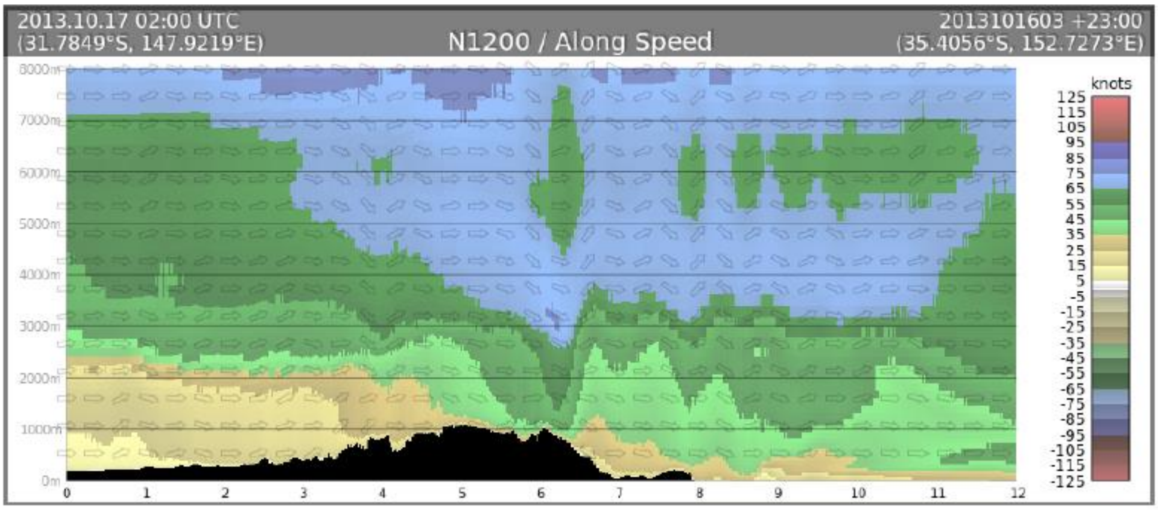

Fig. 4: Cross-section of horizontal wind in the plane shown by the grey line in Fig. 3. Note the tongue of strong winds extending towards the surface near and to the east of position 6, which identifies the fire ground. The downstream signature of mountain waves can be seen also in the open arrows, which represent the direction of air motion.

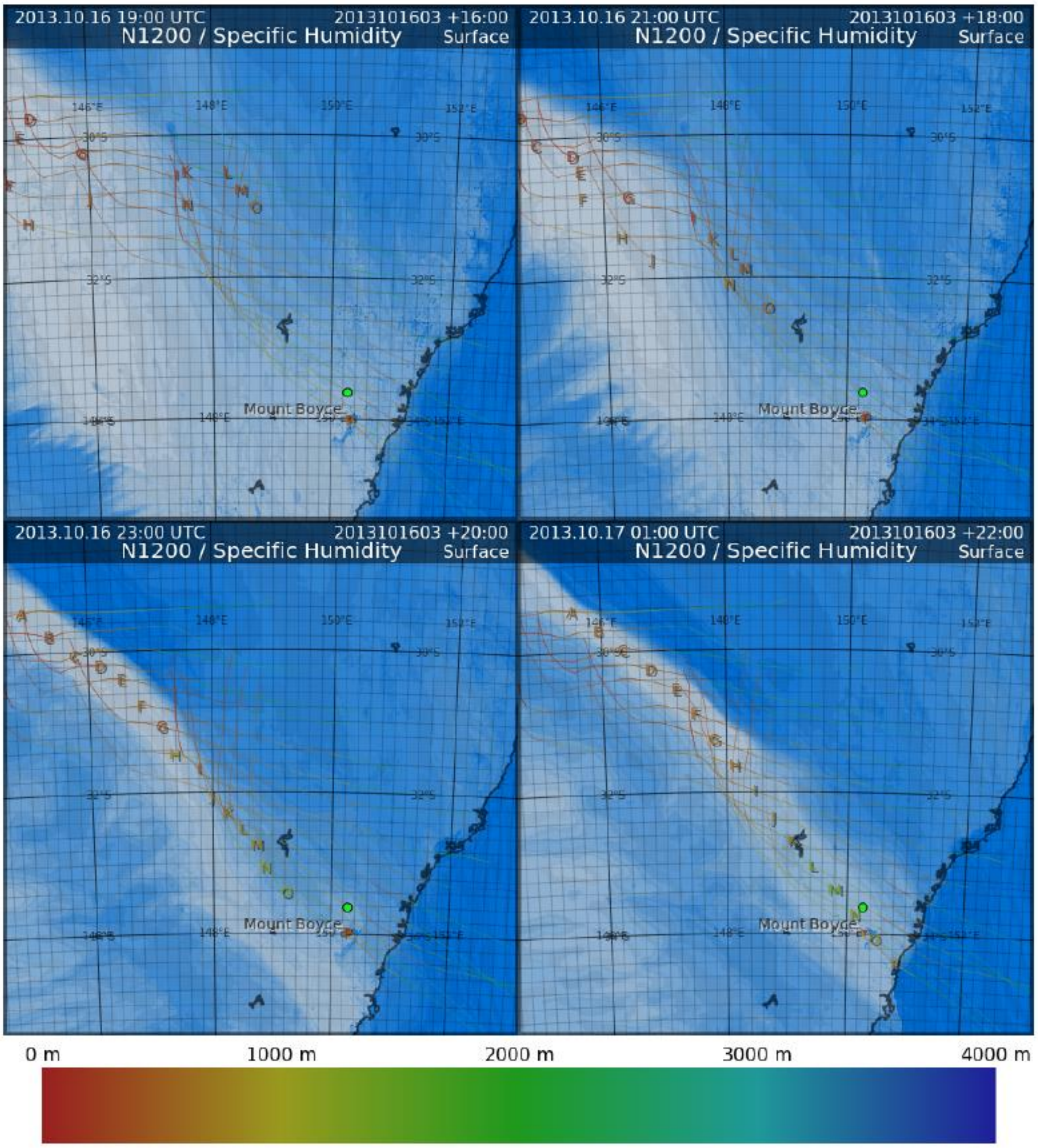

Fig. 5: Simulated surface specific humidity (blue is humid, grey is dry) every 2 hours from 6 am to noon (local time) on 17 October. Note the progression and sharpening of the dry slot as it nears the fire area (green dot). The coloured letters and accompanying lines denote air trajectories, with their colour indicating altitude, showing that the air movement within the slot has little vertical motion.

PYROCUMULONIMBUS

Intense heating by a bushfire causes air to ascend, which if deep enough can cause the formation of cumulus or cumulonimbus clouds in a process known as pyro-convection. This pyro-convection can potentially have a significant impact on fire behaviour by amplifying burn and spread rates, enhancing spotting through plume intensification and igniting new fires via pyrocumulonimbus (PyroCb) lightning.

Last year we reported on early experiments in which pyrocumulus and PyroCb clouds were simulated using a large-eddy model (LEM). We reported that hotter fires in moister background environments produce larger and more intense pyro-convective clouds, including PyroCumulus that produced rainfall and intense downdrafts. These initial experiments did not include a fire moisture source. Fires produce moisture as well as heat, through the evaporation of water trapped in the fuel and through the chemistry of combustion. The role of moisture in PyroCb development is an area of scientific controversy. Accordingly, since the last report the LEM simulation parameter space was increased to include varying amounts of fire moisture, and all simulations were examined in more detail. This includes an analysis of a potentially hazardous downburst and an assessment of the importance of fire moisture in PyroCb development.

Fig. 6 shows a plan view of surface horizontal wind speed at multiple times beginning shortly after the first element of a PyroCb generated downburst impacted the surface, and a wind speed time-series at a single point in the domain (indicated by the black diamond in panels a—d). Panels a—d illustrates multiple bursts of intense winds radiating outwards from the downburst impact sites, and panel e shows multiple surges in wind speed that might be experienced on a hypothetical fire ground. Importantly it shows that the "downburst" is essentially a cluster of downward accelerating cold air masses, with multiple impact sites that lead to a sustained period of strong wind surges (~ 40 minutes in this simulation), which differs from the popular conceptual model of a single downburst with a single outwardly radiating wind surge. Each surge has the potential to increase the rate of fire spread and alter the direction, especially on fire flanks, where firefighters might be located.

The impact of fire moisture on PyroCb development was investigated by adding surface moisture fluxes at the heat source. The heat to moisture ratios were chosen to represent a range of theoretically determined realistic values (Luderer et al. 2009). The driest scenario showed the fire moisture had no discernible impact on PyroCb development, and the wettest scenario had a noticeable but nevertheless minor impact on PyroCb development. The wet scenario is illustrated in Fig. 7, which shows a time-height plot of moisture content in the vicinity of the fire source and plume. The fire moisture is evident in the blue shades, with the background (environmental) moisture value of $4\ g\ kg^{-1}$ apparent in yellow. The dilution of the fire moisture with height is apparent in the lightening shades of blue. Even for this very moist fire, the fire moisture has become so dilute at the condensation level (about 4—4.5 km) that the moisture content only exceeds the environmental concentration for brief periods at about 40 and 65 minutes. This result is consistent with a number of recent observational studies that found fire moisture had no discernible impact on PyroCb development, but does leave open the possibility of greater importance if the boundary layer is relatively shallow.

We have prepared a review of PyroCb forecasting techniques. As there is little published in this area, we also surveyed operational experts in Australia and North America. We found that due to a lack of wild fire observations of plume gas composition, and insufficient understanding of plume dilution rates, existing PyroCb forecast techniques are necessarily ad-hoc, especially when estimating how much fire heat and moisture is required to generate PyroCb. The most promising technique is a recently proposed one that provides an objective estimate of the fire heat required. The technique also estimates the PyroCb condensation level, and the amount of convective instability. Knowledge of the estimated condensation level and fire heat could be used by forecasters to estimate relative fire size, fire intensity, and plume structure required for the PyroCb to be initiated. Once initiated, the convective instability can be used to estimate potential PyroCb intensity. Based on our review, we have developed a broad range of future LEM experiments that will improve our understanding of these important aspects of PyroCb development, including the sensitivity of PyroCb development to fire size and intensity, atmospheric environment and plume structure. These experiments will inform our development and refinement of a prototype forecasting technique.

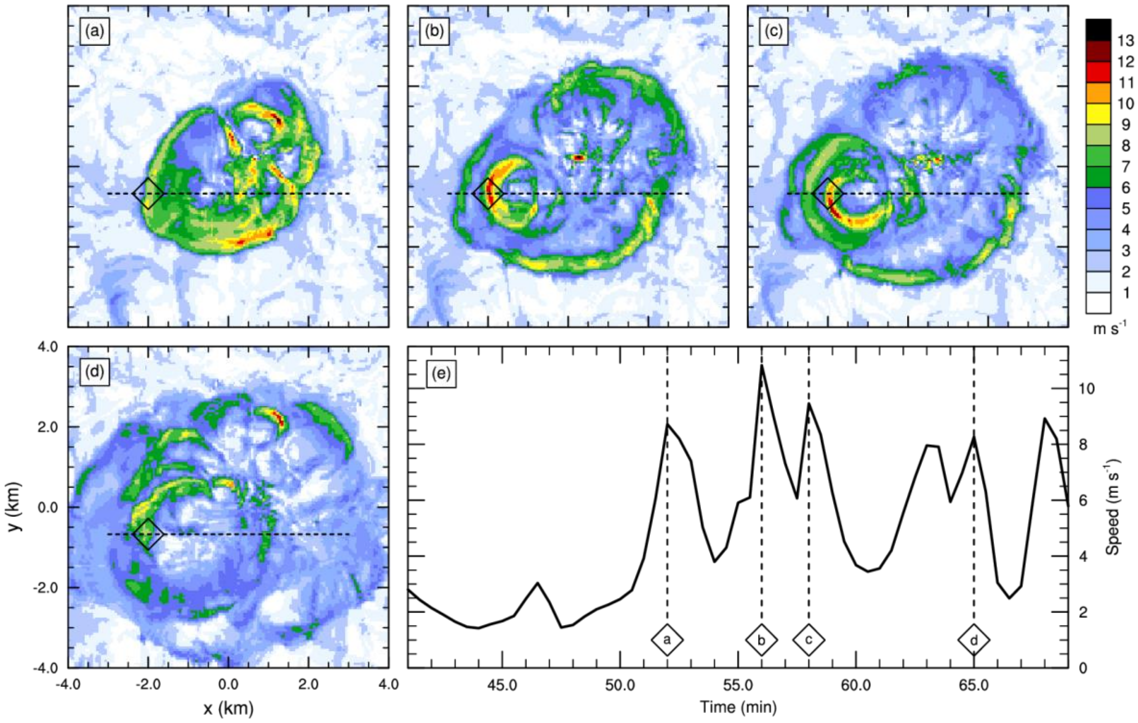

Fig. 6: (a)—(d) Simulated surface horizontal wind speed (shaded) at approximately 8—10 minute intervals, during the impact of a downburst cluster. (e) Wind speed time series at the black diamond location in panels (a)—(d).

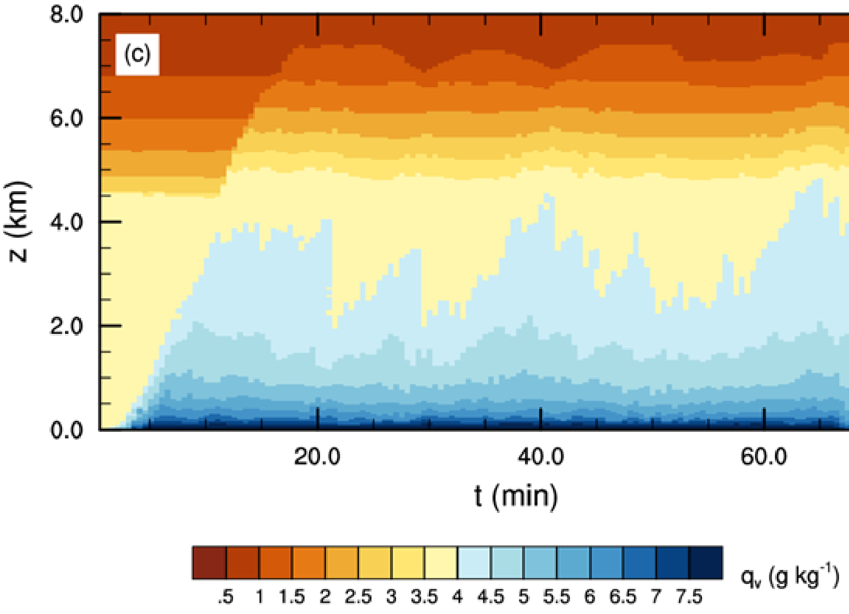

Fig. 7: Time height profile of moisture content for a LEM simulation with a constant boundary layer (lowest 4 km) moisture content of 4 $g\,kg^{-1}$ decreasing linearly above. A circular heat and moisture source of 250 m radius was added in the first few minutes with heat and moisture fluxes of 30 and 11.4 $kW\,m^{-2}$ respectively, corresponding to a theoretically determined "wettest" fire scenario.

EAST COAST LOW OF APRIL 2015

During autumn and winter months the eastern coast of Australia is periodically affected by rapidly developing and intense extratropical low-pressure systems that are known as East Coast Lows (ECL). They form preferentially at night and although they are most common during winter months, they can occur at any time of the year. ECLs bring damaging winds and heavy rainfall with flooding that can last for several days. Due to their rapid development, many issues occur in forecasting these events; such as location along the coast, the intensity and location of maximum winds and rainfall (Mills et al. 2010). The use of ensembles can help in overcoming these challenges and improve forecasts, and also to get a better understanding of how these systems form.

The event that is studied in this project occurred during 20-23 April 2015, with the worst impact on 21 April. It was a devastating event for Dungog and Maitland area, with at least 4 deaths reported and widespread damage. Most recently, the first week of June 2016 saw another ECL develop that moved from central Queensland all the way to Tasmania, causing heavy rain, flash flooding and severe coastal erosion. This emphasises the importance of studying these events in order to understand the dynamics and improve our ability to predict these events, which should also assist in decision making for emergency services.

In the last report, the set up and design of ensemble simulations with 24 members using ACCESS global ensemble model was summarised. The finest resolution in the model was 1.3 km, which sufficed to capture the dynamics of the event. Preliminary analysis of the ensemble simulations in that report showed that forecast rainfall (averaged over the 24 ensemble members) is in good agreement with observed rainfall, even though rainfall in the Dungog area is not as heavy as observed. Nonetheless, the ensemble identifies Dungog as the area at significant risk of extreme rainfall.

Since then, the focus has been on analysing radar and satellite data to get a broader picture of the event, as well as analysing ensemble members in order to understand the dynamics and predictability of the event. Figure 8 shows radar image at 1336 UTC 20 April 2015 (+ 10 hours for local time), where cyclonic rotation of the cloud band is evident as well as bands of intense convection that are associated with heavy rain. Animations of radar images also show a second low forming that crosses over the Dungog area after 0600 UTC 21 April 2015. For ECLs, the strongest winds usually occur to the south of the main low centre which is confirmed by scatterometer wind fields for this event (Fig. 9); cyclonic rotation close to the coast is also evident in this figure.

ECL development is characterised by the interaction of a pre-existing trough of low pressure ("easterly dip") and an upper-tropospheric cut-off low. Often, many small vortices form within the main low, and these can bring the worst weather. Figure 10 shows 1200 UTC 20 April 2015 near-surface (1 km) and upper-level (10 km) flow comparison for one of the ensemble members. Strong southeasterly near-surface winds are seen to the south of the main low in Fig. 10a, and small vortices begin to form along the shear line. At upper levels there is a negatively tilted (towards the northeast) trough that moves toward the coast, with a strong northwesterly jet to the northeast of the upper-level trough (Fig. 10b). This pattern seems to be common for most ECLs (Mills et al. 2010).

During the analysis of satellite images a distinctive pattern of cloud transverse banding associated with the main ECL cloud band was observed. Such cloud systems are known as "striated deltas", due to their triangular or delta and banded appearance, and are thought to often be associated with intense surface cyclogenesis (Feren 1995). Figure 11 shows this striated delta cloud at 1232 UTC 20 April 2015, which formed over the Tasman Sea and disappeared after few hours. Comparison with Fig. 10b shows that it occurs within the diffluent northwesterly flow in the jet exit region. Feren (1995) suggested that the striations are tracers of inertia-gravity waves and we are currently using ensemble simulations to understand the source mechanisms of these striations and their relationship to the ECL event.

In addition to the aforementioned analyses, we are continuing to learn from ensemble simulations about predictability of the event and how to use this information to benefit both forecasters and emergency services personnel.

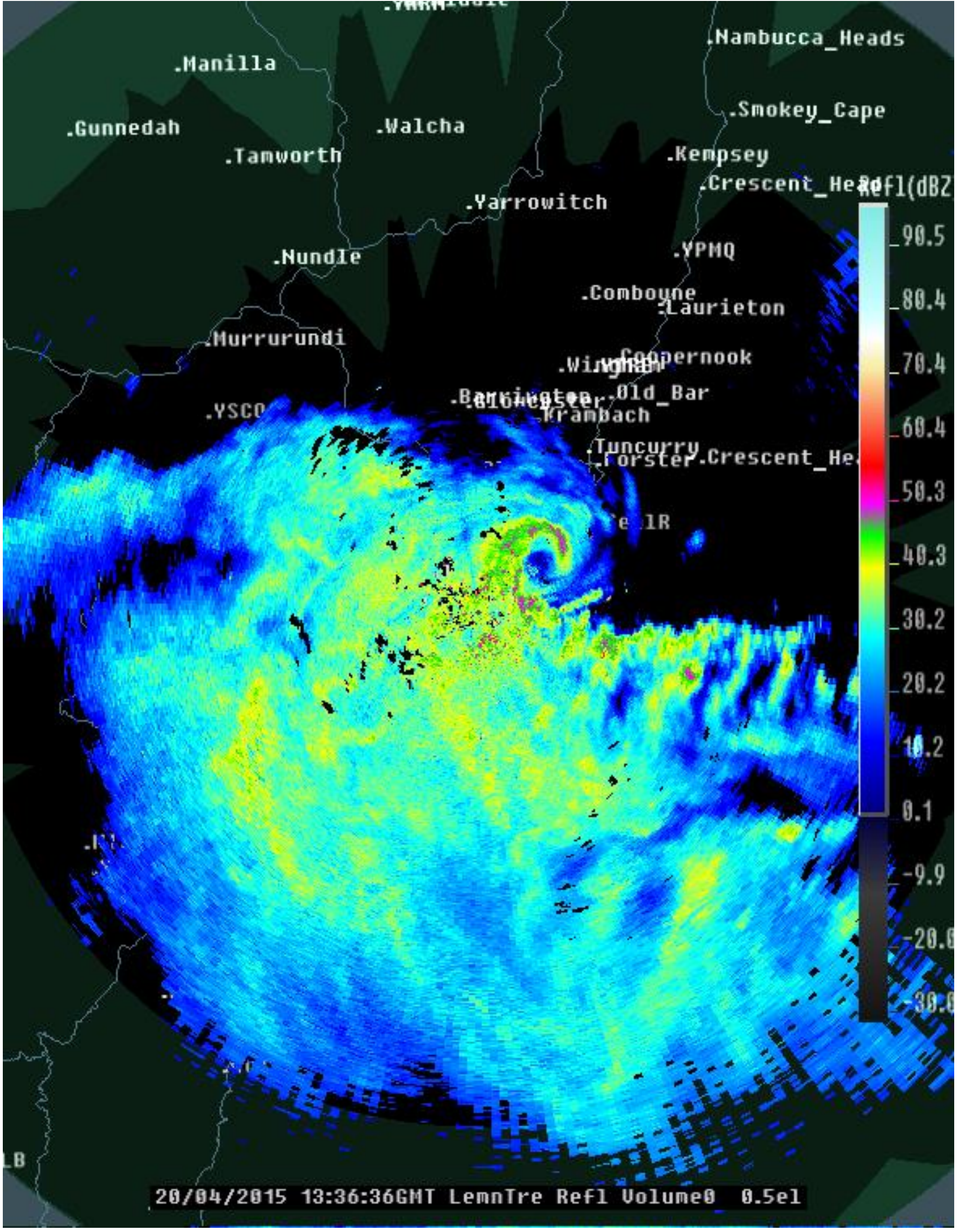

Fig. 8: Radar reflectivity (dBZ) for 1336 UTC 20 April 2015. Cyclonic rotation of the cloud band associated with the East Coast Low is evident, as well as the area of intense convection.

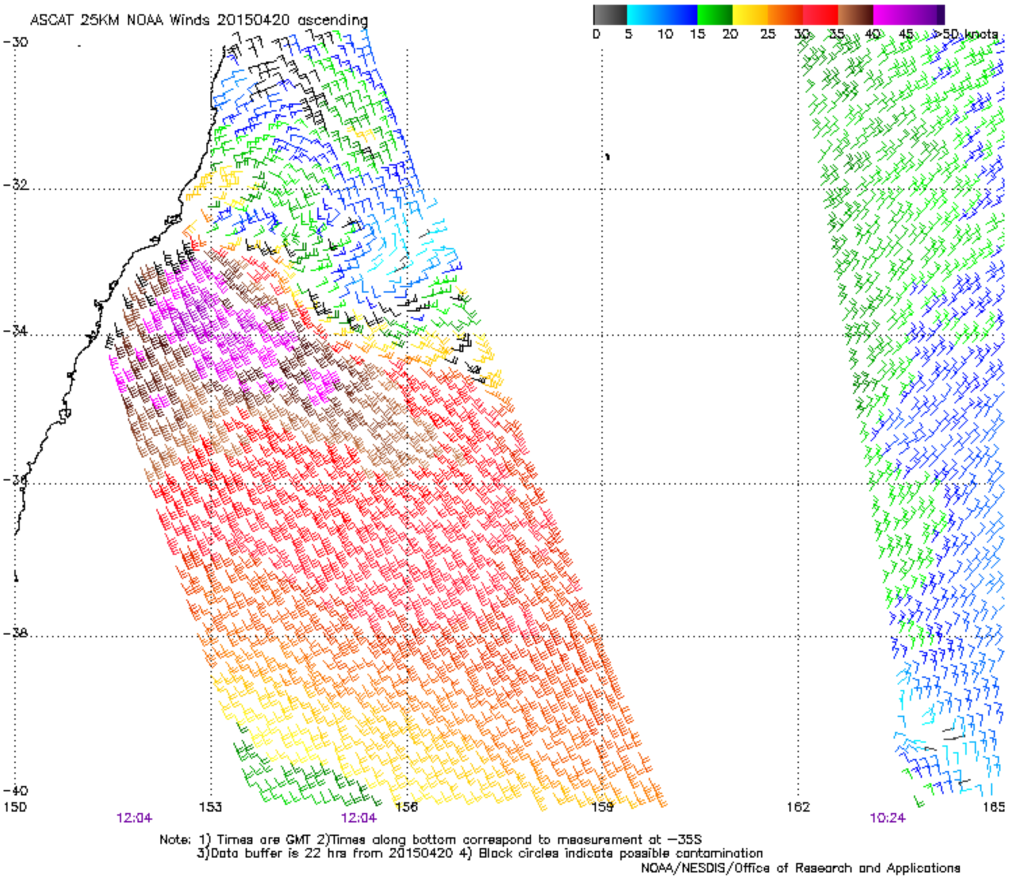

Fig. 9: Scatterometer wind fields for 20 April 2015. Note cyclonic rotation of the winds, and strong southeasterly winds to the south of the low centre.

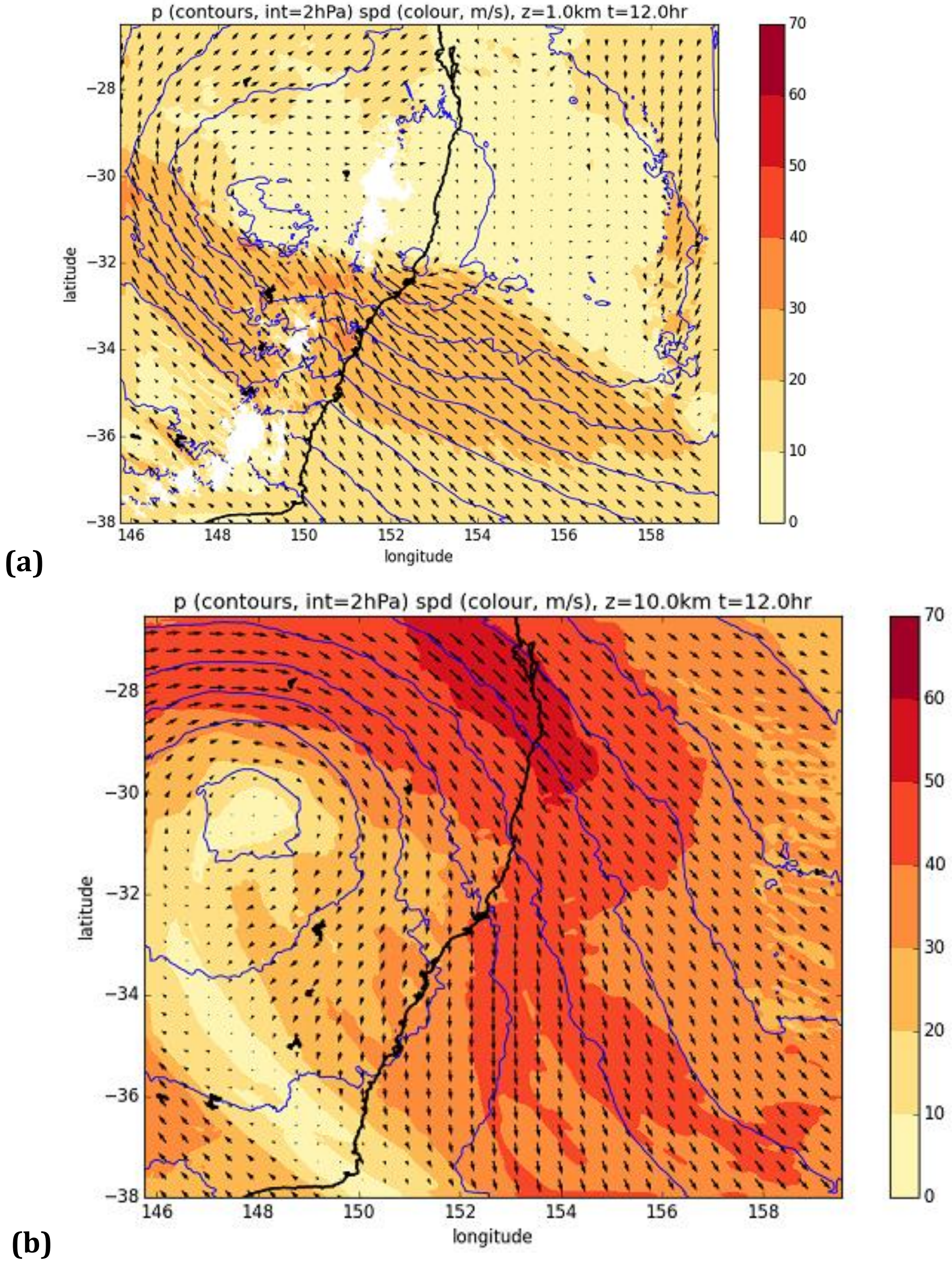

Fig. 10: 1200 UTC 20 April 2015 simulated winds (m/s) and pressure (hPa) for one of the ensemble members at (a) z = 1 km and (b) z = 10 km. Note in (b) the negatively tilted (towards the northeast) trough and strong northwesterly jet.

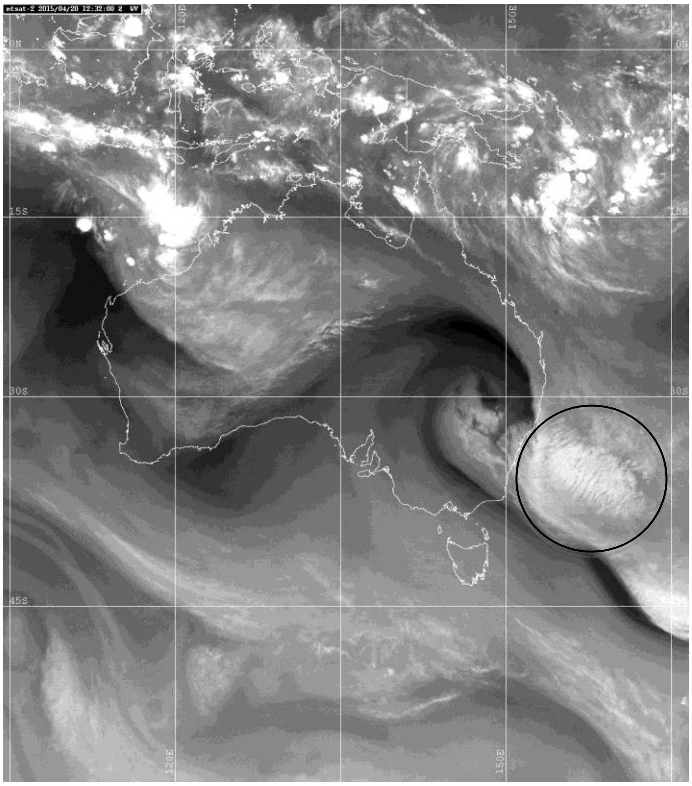

Fig. 11: 1232 UTC 20 April 2015 water vapour satellite imagery, showing the "striated delta" cloud banding over the Tasman Sea (black circle).

PUBLICATIONS LIST

JOURNAL PAPERS

Ching, E., R.J.B. Fawcett, K.J. Tory, W. Thurston and J.D. Kepert, 2016: Mesoscale features related to the Blue Mountains fires of 17 October 2013 revealed by high resolution numerical weather prediction (NWP) modelling. For submission to *Monthly Weather Review*.

Thurston, W., J.D. Kepert, K.J. Tory and R.J.B Fawcett, 2016: The contribution of turbulent plume dynamics to long-range spotting. For submission to *I. J. Wildland Fire*.

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William Thurston, Kevin J. Tory, Robert J. B. Fawcett and Jeffrey D. Kepert, 2015: Large-eddy simulations of pyro-convection and its sensitivity to environmental conditions. *Proceedings of the research forum at the Bushfire and Natural Hazards CRC & AFAC conference*, Adelaide, South Australia. September 2015.

W. Thurston, K.J. Tory, R.J.B. Fawcett and J.D. Kepert, 2016: Large-eddy simulations of pyro-convection and its sensitivity to moisture. *Proceedings of the 5th International Fire Behaviour and Fuels conference,* Melbourne, April 2016.

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Kevin J. Tory and William Thurston, 2015: Pyrocumulonimbus: A literature review. *Bushfire And Natural Hazards CRC report.*

INVITED CONFERENCE PRESENTATIONS

J.D. Kepert, M. J. Naughton and J. Bally. *Managing Severe Weather – Progress and Opportunities. Invited presentation at BNHCRC and AFAC Conference September 2014.*

J. D. Kepert. *The role of the boundary layer in tropical cyclone dynamics.* Eighth International Workshop on Tropical Cyclones, Jeju, Sth Korea, December 2014.

J. D. Kepert. *Why use ensemble prediction?* Invited keynote presentation for BNHCRC and AFAC Conference September 2016.

AUSTRALIAN METEOROLOGICAL AND OCEANOGRAPHIC SOCIETY ANNUAL CONFERENCE, JULY 2015

Modelling the fire weather of the Blue Mountains fires of October 2013. Robert J. B. Fawcett, Simon E. Ching, William Thurston, Kevin J. Tory and Jeffrey D. Kepert. Poster presented at the AMOS conference, Brisbane, July 2015.

Large-eddy simulations of pyro-convection and its sensitivity to environmental conditions. William Thurston, Kevin J. Tory, Robert J. B. Fawcett and Jeffrey D. Kepert.

Long-range spotting by bushfire plumes: The effects of in-plume turbulence on firebrand trajectory. William Thurston, Kevin J. Tory, Robert J. B. Fawcett and Jeffrey D. Kepert

BUSHFIRE AND NATURAL HAZARDS CRC AND AFAC CONFERENCE, SEPTEMBER 2015

Modelling the fire weather of the Blue Mountains fires of October 2013, S E Ching, R J B Fawcett, W Thurston, K J Tory, J D Kepert. Poster presented at the BNHCRC and AFAC September 2015

Meteorology of the Sampson Flat fire, S Slattery, M Peace, K Egan, R J B Fawcett, J D Kepert. Poster presented at the BNHCRC and AFAC September 2015

Fire weather forecasting – research to operations. M. Peace, J D Kepert and J Bally

William Thurston, Kevin J Tory, Robert J B Fawcett and Jeffrey D Kepert, 2015: Large-eddy simulations of pyro-convection and its sensitivity to environmental conditions.

Michael Foley, Mika Peace, Deryn Griffiths, James Sofra and Jeffrey Kepert: The Sydney 2014 Forecast Demonstration Project – A step from research to operations.

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Long-range spotting by bushfire plumes: The effects of in-plume turbulence on firebrand trajectory, by William Thurston, Kevin J Tory, Robert J B Fawcett and Jeffrey D Kepert.

CAWCR ANNUAL MODELLING WORKSHOP, OCTOBER 2015

Kepert, J.D., R.J.B. Fawcett, E. Ching, W. Thurston and K.J. Tory. High-resolution ensemble prediction of an east coast low.

BUSHFIRE WORKSHOP, MONASH UNIVERSITY, JANUARY 2016

The effect of turbulent plume dynamics on ember transport. William Thurston, Kevin J Tory, Robert J B Fawcett and Jeffrey D Kepert

The importance of fire moisture to PyroCumulus development. William Thurston, Kevin J Tory, Robert J B Fawcett and Jeffrey D Kepert

AUSTRALIAN METEOROLOGICAL AND OCEANOGRAPHIC SOCIETY ANNUAL CONFERENCE, FEBRUARY 2016

High-resolution ensemble prediction of an East Coast Low. Jeff Kepert, Robert Fawcett, Simon Ching, William Thurston and Kevin Tory

Time and space scales in the tropical cyclone boundary layer. Jeffrey D. Kepert

Kepert, J.D., R.J.B. Fawcett, E. Ching, W. Thurston and K.J. Tory. High-resolution ensemble prediction of an east coast low. Presented at the AMOS Annual Conference, Melbourne, 8 – 11 February 2016.

5TH INTERNATIONAL FIRE BEHAVIOR AND FUELS CONFERENCE, APRIL 2016

Large-eddy simulations of pyro-convection and its sensitivity to moisture, W. Thurston, K.J. Tory, R.J.B. Fawcett and J.D. Kepert

Long-range spotting by bushfire plumes: The effects of plume dynamics and turbulence on firebrand trajectory, W. Thurston, K.J. Tory, R.J.B. Fawcett and J.D. Kepert

Mesoscale Features Related to the Blue Mountains Fires of 17 October 2013 Revealed by High Resolution Numerical Weather Prediction (NWP) Modelling by S.E. Ching, R.J.B. Fawcett, W. Thurston, K.J. Tory and J.D. Kepert. *Paper presented at the Fire Behaviour and Fuels conference*, Melbourne, April 2016.

BOM R&D SEMINAR SERIES

Why is the tropical cyclone boundary layer not well mixed? Jeffrey Kepert, 29th June 2016

The effect of turbulent plume dynamics on ember transport. William Thurston, 6th April 2016

Large-eddy simulations of pyro-convection and its sensitivity to environmental conditions. William Thurston, 4th November 2015

High resolution modelling of the meteorology of the Blue Mountain bushfires of October 2013. Simon Ching, 16th October 2015

OTHER

Modelling the Fire Weather of the Blue Mountains Fires of 17 October 2013. Simon E. Ching, Robert J. B. Fawcett, William Thurston, Kevin J. Tory and Jeffrey D. Kepert. *Paper presented at the Centre for Australian Weather and Climate Research*, 19 – 22 October 2015.

CURRENT TEAM MEMBERS

Jeff Kepert: Project leader. Tropical cyclones, atmospheric dynamics, fire weather, turbulence.

Kevin Tory: Project co-leader. Tropical cyclones, atmospheric dynamics, pyrocumulus, fire weather.

Will Thurston: Large eddy modelling, plume behavior, pyrocumulus, ember transport, visualization.

Dragana Zovko-Rajak: East coast lows, severe thunderstorms, turbulence.

Simon (Eng) Ching: Mesoscale meteorology, fire weather, visualization.

Robert Fawcett: ACCESS modelling, climatology, heat waves, fire weather.

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