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ACCESS-Fire: coupled fire-atmosphere modelling

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ABSTRACT

Coupled models are a class of fire prediction models that integrate a fire component with an atmospheric component, to examine how the energy released by a fire modifies the surrounding atmosphere. Coupled models can resolve complex interactions between the fire, topography and atmosphere, which subsequently manifest on fire behaviour. Results from simulations promote understanding of the driving processes in dynamic fire events. This can inform development of predictive tools that may be used to anticipate extreme fire behaviour and mitigate against the impacts of significant fires.

Globally, several coupled models have been developed; mostly by meteorological institutions for application in a research capacity. They can be broadly separated as taking either physical or empirical modelling approaches. We are running ACCESS-Fire; an empirical coupled model. It links the research version of the Australian Community Climate and Earth-System Simulator (ACCESS) Numerical Weather Prediction (NWP) to a set of empirically derived fire spread equations. In this presentation we will describe the coupled fire-atmosphere model ACCESS-Fire and report on progress on simulations of recent significant fire events.

In Australia and overseas, the imperative for accurate, flexible and timely predictions for prescribed (fuel reduction) burns and bushfires will only increase. Incorporating complex, dynamical meteorological fields is a critical component in building fire prediction systems that can resolve some of the most destructive elements of fire behaviour. Although coupled fire-atmosphere models are currently limited in producing timely operational output due to computational requirements, these restrictions will diminish as technology capabilities continue to increase.

Fire atmosphere interactions

Large bushfires release substantial amounts of energy into the surrounding atmosphere. This energy release modifies the structure of the surrounding wind, temperature and moisture profiles in space and time. The changes driven by the fire can manifest as winds that are similar in speed but opposite in direction to the prevailing winds, pyrocumulus clouds and, in extreme cases, pyro-cumulonimbus clouds. The dynamic feedback loops produced by the fire-atmosphere coupling process can have a dramatic influence on how a fire evolves. Fire-atmosphere feedbacks can also be strongly enhanced by local topographic influences due to wind flow being modified through high terrain.

In current operational fire simulation models used in Australia, simple meteorological values are provided as inputs to an algorithm for fire spread which produces a prediction of fire perimeter evolution across a two-dimensional landscape. This approach does not incorporate any three-dimensional interactions between the fire and atmosphere and, in certain cases, will provide a limited depiction of how a fire may evolve, particularly in a dynamic environment in high terrain. This project explores the ability to examine fire-atmosphere interactions through use of a coupled model.

We use the premier operational and research Australian high-resolution weather prediction model ACCESS, which has been coupled to a set of empirical fire-spread models including McArthur forest, McArthur grassland, CSIRO forest (Vesta) and Rothermel. The modelling framework allows for inclusion of any similar empirical fire model. The ACCESS model (uncoupled) has been used to examine several high impact fire events and has provided detailed insights into the meteorological processes impacting a fire environment. Coupling ACCESS to a fire model provides opportunity for future development of a coupled modelling capability in Australia, as well as potential to provide a fire prediction tool to international partners through the overarching UK Met Office Unified Model framework.

We have selected two case studies to simulate and analyse with ACCESS-Fire with the objective of better understanding and prediction of fire-atmosphere feedback processes and demonstrating the skill and usefulness of the coupled model. Fire-atmosphere feedback is important because it often reflects a transition from steady-state fire spread to rapidly fluctuating, dynamic and more intense fire activity, which is inherently more difficult to predict. Blow-up fires, extreme fire behaviour and dynamic fire behaviour are all terms that may be used to describe fire activity that is erratic and potentially dangerous to firefighters and destructive to communities. Coupled model results have been shown to assist in identifying and the triggers and ingredients that lead to non-linear fire activity. This knowledge will enable risk mitigation activities to be undertaken; both at bushfires and fuel reduction burns.

Coupled fire-atmosphere models are increasingly being used internationally in both research and operational spheres. The most progressive operational implementation is in the USA state of Colorado, where the WRF-Fire model is a component of a new capability for fire prediction in the state. Other USA work includes using the WRF-Fire model for predicting particulate trajectories in fire plumes.

A coupled fire-atmosphere model has also been used to analyse fire behaviour in Mediterranean fires. As Australia has one of the most fire-prone landscapes in the world, with critical infrastructure and homes in high risk areas, and with climate projections indicating an increase in fire risk in landscape, our requirement for developing capability in this space is unparalleled.

ACCESS-Fire model developments

Coupling a fire model to the ACCESS model was a project originally conceived in a collaboration between Melbourne and Monash universities with the objective of simulating the Black Saturday fires (Toivanen et al. 2018). The fire code that was written during the Monash project was provided to BoM and our simulations are run on NCI. The original code was configured for a single event and implemented in the now-retired UMUI ACCESS model interface. Significant effort has been invested in modifying the code to run on multiple events and in transitioning to the new, more interactive and intuitive Rose-Cylc model user interface. Ongoing development work will continue to build the model's functionality, capability and predictive skill.

A significant development challenge we have overcome is selecting the appropriate settings for the atmospheric boundary layer to ensure model stability. Because ACCESS is a global numerical weather prediction model, it was not designed to handle the energy fluxes from a large fire at resolutions of ~100 m; in particular, ACCESS was not intended or designed to resolve the turbulent mixing processes required to disperse the fire's energy through the near-surface atmospheric grids.

The settings for the boundary layer model configuration have undergone significant testing in order to determine the most appropriate options to maintain model stability.

The ACCESS-Fire model continues to be under development and further testing of the model configuration and capabilities is required. In its current form, it is a research model which can be used to explore the atmospheric processes surrounding bushfires and deliver proof-of-concept of the value of a coupled framework for simulating landscape-scale wildfires. Although a future transition to operational application is possible, it is not imminent due to the effort required to develop and test such a capability.

Case studies

In our presentation, we show initial results from two case studies that have been selected in consultation with our partners in fire and land management agencies (Fig. 1 and Fig. 2). The Waroona fire in southwest Western Australia in January 2016 is the first case study. Over a two-day period, there were four extreme fire behaviour events; two separate pyro-convective thunderstorms and two evening ember storms.

The Sir Ivan fire in NSW is the second case study. The fire occurred on a day of 'catastrophic' fire danger and produced a pyrocumulonimbus cloud when the environmental wind direction changed from northwest to southerly. An unprecedented, detailed set of observations were collected during the event by NSW RFS and these will be a valuable component in the analysis.

Waroona fire

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

During the first two days of the fire, there were four episodes of extreme fire behaviour. Two separate pyrocumulonimbus (pyrocb) events developed; both produced anomalously fast runs in the prevailing winds and lightning from the first pyrocb was observed to ignite new fires. The second pyrocb event occurred at a time that is outside the normal diurnal timing of thunderstorms. Two evening ember storms occurred; the first impacted the town of Waroona and the second caused devastation when it devastated the town of Yarloop. The ember storms were driven by fire plumes interacting with local downslope winds; resulting in a turbulent horizontal transport mechanism conducive to lofting and transport of numerous firebrands. None of the four episodes of extreme fire behaviour matched the time of highest fire danger as measured by fire danger indices.

The first pyrocb on 6 January was triggered by the passage of a sea breeze front and developed a deep plume to higher than 14 km. Lightning from the pyrocb ignited new fires downwind and a density current outflow was observed at a nearby Automatic Weather Station (AWS). On 7 January, the second pyrocb developed during late morning, triggered by high energy release along a 20 km fire line.

On the evening of 6 January, the town of Waroona was reported to be under ember attack at around 2100 hr. The ember attack is likely to have been a result of lighting ignition of a new fire closer to the town, which was subsequently driven by a density current outflow from the pyrocb. Downslope winds provided a localised lofting, transport, and turbulent dispersion mechanism for firebrands, and produced the ember attack over Waroona. On 7 January a second evening ember storm occurred, which effectively destroyed the town of Yarloop. The ember storm over Yarloop was similarly driven by downslope winds. Heavy, long unburnt fuels to the east of the town were a significant contributing factor to the intensity of the fire as well as being a source of firebrands. Doppler radar velocity scans show significant vertical plume development and localised convergence at the time Yarloop was destroyed by the ember storm.

On both evenings, the fire was burning on the lee slopes of the Darling escarpment, consequently, local downslope winds and topographic effects played an important role in driving the fire activity and the evening ember showers.

An important aspect of the dynamics of downslope winds in driving ember showers is their highly turbulent nature, which is conducive to spotting and ember showers, particularly if local fuels are favourable for firebrand production. Slow overnight fuel moisture recovery in the hot, dry conditions would also be a contributing factor.

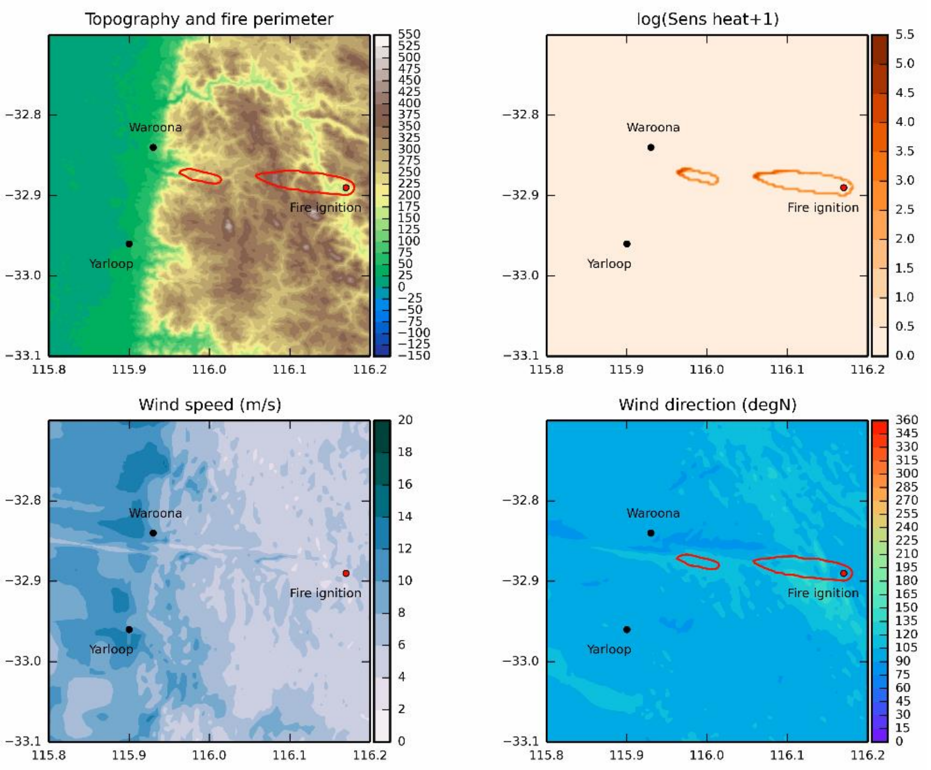

Figure 1: Simulation of the Waroona fire, shown at 2251LT Local Time 6 January 2016. Top left: topography and fire perimeter. Top right: sensible heat flux from the fire grid (logarithmic scale). Bottom left: wind speed. Bottom right: wind direction.

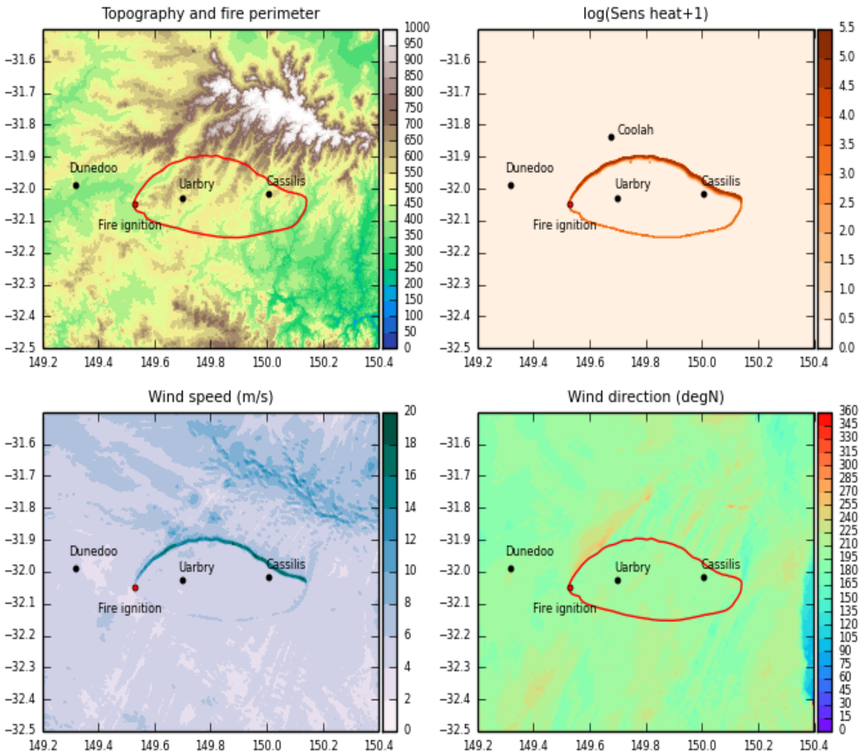

Figure 2: Simulation of the Sir Ivan fire, shown at 2116 LT, Sunday 12 February 2017. Top left: topography and fire perimeter. Top right: sensible heat flux from the fire grid (logarithmic scale). Bottom left: wind speed. Bottom right: wind direction.

Sir Ivan fire

The Sir Ivan fire burnt 55,000 ha in NSW on Sunday 12 February 2017, on a day when temperature records were broken during the worst fire weather conditions recorded in that state. A synoptic wind change in the mid to late afternoon turned winds from the northwest to the southwest and consequently changed the direction of fire spread and extended the length of the head fire. The wind change triggered development of a pyrocb, the lightning strikes from which ignited new fires downwind.

Due to advances in Numerical Weather Prediction (NWP) modelling over the past decades, accurate weather information is now produced at high spatial and vertical resolution. Consequently, the dangerous fire weather conditions were anticipated several days ahead, and communicated to fire agencies with a high level of confidence. However, the quantity of energy released by a fire the size and scale of the Sir Ivan fire will create a response in the surrounding atmosphere and capturing these processes is fundamental to understanding the complex environment.

During the Sir Ivan fire an extensive set of observations were taken, including detailed fire progression maps. These will be compared against our simulations to assess the skill of ACCESS-Fire simulations and explore how well the coupled fire-atmosphere model captures the influence of the fire's energy release in high terrain. A key question to examine is whether the coupling processes have a quantifiable influence on fire behaviour at particular stages of fire progression and whether features in the model results reconcile with the available observations.

Simulation results

We have performed simulations of both the Waroona and Sir Ivan fires, which from initial assessments have produced a very reasonable match against the reconstructed fire spreads. Simulations to date have used the CSIRO forest fuel (Vesta) fire spread model, and constant fuel loads, which is appropriate for the Waroona fire, but will be adjusted to variable fuels for Sir Ivan. Fire fields have been output at time steps of one minute, animations of which will be shown at the conference. Atmospheric data is output at longer intervals and more detailed analysis of the atmospheric fields will be explored once the fire simulations are optimal. Future analysis will include examining detail of processes such as the pyro-convection, ember storm dynamics and synoptic wind change.

Next phase

Comparison of our simulated fire perimeters has been subjective and, although our initial assessment is that the output is agreeably well matched with the observed perimeters, more formal verification is required and will be conducted during subsequent work. The verification will match fire output to the available time steps of the reconstructions prepared by DPAWs and RFS. The verification may prompt subsequent runs that attempt to capture fuel discontinuities, mitigation efforts or natural fire breaks. However, it is not the intent of our current work to produce a 'perfect' reconstruction but to explore the dynamical processes surrounding the extreme fire behaviour.

There are limitless options and questions to pursue with the analysis of the two fires and testing the capabilities of the modelling framework, however we intend to focus on the following questions:

Waroona

Figure 1 shows initial simulations of the Waroona fire. Our subsequent simulations will be increments initialised from known perimeters. The initial simulations have implemented a single fire ignition, which then ran for ~2 days to capture the periods of extreme fire behaviour. However, this is not a sound approach to modelling fire spread as it produces day-by-day compounding errors in the fire perimeter and is an unrealistic and impractical modelling approach. A more sensible approach is to re-initialise the fire perimeter from a known boundary at appropriate intervals, which would typically be at around 6-12 hours. Such an approach is consistent with regular re-starts, as performed in USA operations and in Australia using the Phoenix model.

We intend to initialise Waroona at three time points. The first will be the time of initial ignition (or fire identification), with the simulation continuing into the evening in order to capture the evening ember shower (12+ hours, similar to our current run). The second start will be the morning of 7 January, with the objective of providing an initial state to capture the extreme fire behaviour and unexpectedly fast rate of spread during the morning, which is hypothesised to be through entrainment of a meteorological low-level jet. The third restart will be late afternoon or early evening on 7 January, before the onset of the evening ember shower.

With this set of three simulations, we aim to examine the processes surrounding the two evening ember showers and the morning fire run on 7 January.

Sir Ivan

Our early runs (including Fig. 2) have used a constant fuel regime, which is a poor representation of the landscape the fire burned across. Detailed maps have been provided by RFS; these mosaic fuel maps will be implemented for the Sir Ivan fire. The planned analysis will compare the observations and model output, with a focus on comparison of the linescan images and simulated fire heatflux. We also intend to examine the plume depth and plume dynamics near the wind changes when the pyrocb occurred, and further explore a circulation that develops on the fire front post-wind change.

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