Fire-atmosphere coupled numerical simulations show a fire changes the local meteorology

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Abstract

The idea that a fire 'creates its own weather' is supported by observations from fire grounds and results from idealised numerical simulations. We have simulated two Australian bushfires where unexpected fire behaviour occurred, using the coupled fire-atmosphere model WRF-fire. The results present new evidence of dynamical interactions between a fire and the surrounding atmosphere. The simulations are of two fires that burnt on Kangaroo Island, South Australia in December 2007, the D'Estrees fire and the Rocky River fire. In the D'Estrees simulations, fire-atmosphere interactions produced a long-lived fire-induced vortex. In the Rocky River simulations, fire perimeter was sensitive to the local fire-modified winds that arise from interactions between the fire, atmosphere and local topography. A simulation of the Rocky River fire at high temporal resolution produced pulses in the rate of spread of the fire front coincident with the passage of mesoscale convective cells. The simulation results suggest that the potential for extreme fire behaviour arises from interactions between the fire and the atmosphere. These results add to the body of research showing that feedback between a fire and the atmosphere can play an important role in shaping both fire behaviour and micro-scale meteorology. As a consequence, we affirm that a comprehensive risk assessment at a fire-ground should consider the three-dimensional structure of the atmosphere and the possibility of dynamical feedback processes occurring.

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1 INTRODUCTION

Fire-behaviour simulation models are increasingly being used by fire managers in real time, and in future years this use will grow. Operational simulation models presently in application in Australia predict fire spread and other elements of fire behaviour using simple weather variables as input (as well as topography and fuel information), but they do not include direct feedback from the fire to the atmosphere. However, it is well recognised that the heat and moisture generated by a fire can affect the local meteorology. This often manifests as pyro- convective cloud development and modification of wind strength and direction in the fire's vicinity. Perhaps the most dramatic recent example of a fire creating its own weather is the fire tornado generated in the 2003 Canberra fires, documented by McRae et al. (2013). Their study is just one of many showing that the interactions between a fire and the surrounding atmosphere can change the local meteorological environment, with subsequent dramatic impacts on fire behaviour. Factors that are less well understood are the physical processes that lead to these feedback loops, how and when such feedbacks will occur, and of what magnitude they will be. Yet these factors could be of critical importance to fire-ground operations and to firefighter safety. Therefore they should be considered in the context of firstly, pertinent information in fire weather forecasts and secondly, appropriate inputs to fire simulation models.

In order to further current understanding of fire-atmosphere interactions, we have run coupled simulations of two Australian bushfires using the coupled fire- atmosphere model WRF-fire. WRF is described by Skamarock et al. (2008) and the fire component of WRF-fire is described in detail by Mandel et al. (2011). Coen et al. (2013) give a comprehensive description of the model's applications and capabilities. WRF-fire is similar to other numerical simulation fire behaviour models in that the underlying fire spread is formulated using an empirical method, in this case that of Rothermel (1972). However, WRF-fire differs from other operational models because it captures the interactions between the fire and atmosphere. It implements this by calculating a heat flux (sensible heat) and moisture flux (latent heat) from a quantity and type of fuel burnt at each time step of the simulation. These fluxes are passed back into the atmospheric model at the following time step, and the atmospheric response to the fire fluxes is by modification of the local wind fields. Thus, the surrounding atmosphere responds to the energy released by the fire and interactions between the two can be examined. Our simulations have been run in 'feedback on' and 'feedback off' mode. The difference in the two modes is that in the feedback off simulations, no heat and moisture fluxes are passed from the fire model to the atmospheric model, so the atmosphere is effectively unaware of the fire's presence. Comparing the two results allows insights as to the impact of a fire on the surrounding atmosphere and the impact the coupling process has on the fire's evolution. Using a coupled model in this way supplements the observational dataset, which is limited due to the difficulties associated with obtaining detailed three-dimensional observations of wind and temperature in the vicinity of a real fire. Our choice of WRF-fire was due to it being the most accessible and well supported model available for fire-atmosphere simulations and it matches our particular interest in bushfires and mesoscale atmospheric processes.

In this paper we show a selection of preliminary results from the WRF-fire simulations and then discuss some implications of the findings. The work presented here is in progress and a more complete version for publication is in preparation. The prepared work includes detail of the WRF-fire configuration, it discusses the limitations of the simulations, presents a more complete set of references and contains substantially more results. The meteorology and fire behaviour of the D'Estrees and Rocky River fires are described in the case study of Peace & Mills (2012).

2 Results

The simulation results show changes to mesoscale atmospheric structure as a result of the energy released by a fire, and a number of interesting features have been identified. The aim of these simulations was to examine fire-atmosphere interactions arising from the coupling process, rather than verify the simulated fire perimeter against observations. However, we note that the simulated fire isochrones provide a reasonable representation of fire spread against the limited available observations.

Figure 1 shows a series of time steps of the D'Estrees fire. During the event dramatic fire behaviour occurred and satellite imagery showed a well developed smoke column extending to the southwest. Of particular interest was that the fire activity was distinctly different from three other fires burning nearby. In the simulations, a complex sea-breeze frontal wind change moved over the fire ground and a long-lived vortex developed adjacent to the head fire in an area of wind shear associated with the front. The simulated vortex was 1-2 km wide and 500-600 m high and persisted for over five hours of simulation time. When feedback from the fire to the atmosphere was turned off, no vortex developed. Further detail on the simulated vortex is included in the paper in preparation.

The Rocky River fire moved rapidly up a gully in southwest winds and extreme fire behaviour was observed. Figure 2 shows the final fire perimeter for the Rocky River fire simulations. The difference in fire area on the northeastern flank arises from fire-atmosphere coupling and wind convergence along a ridge top. Note that the fire perimeter is smaller for the feedback on case. In comparison (not shown), the fire perimeter for the D'Estrees fire was smaller for the feedback off case.

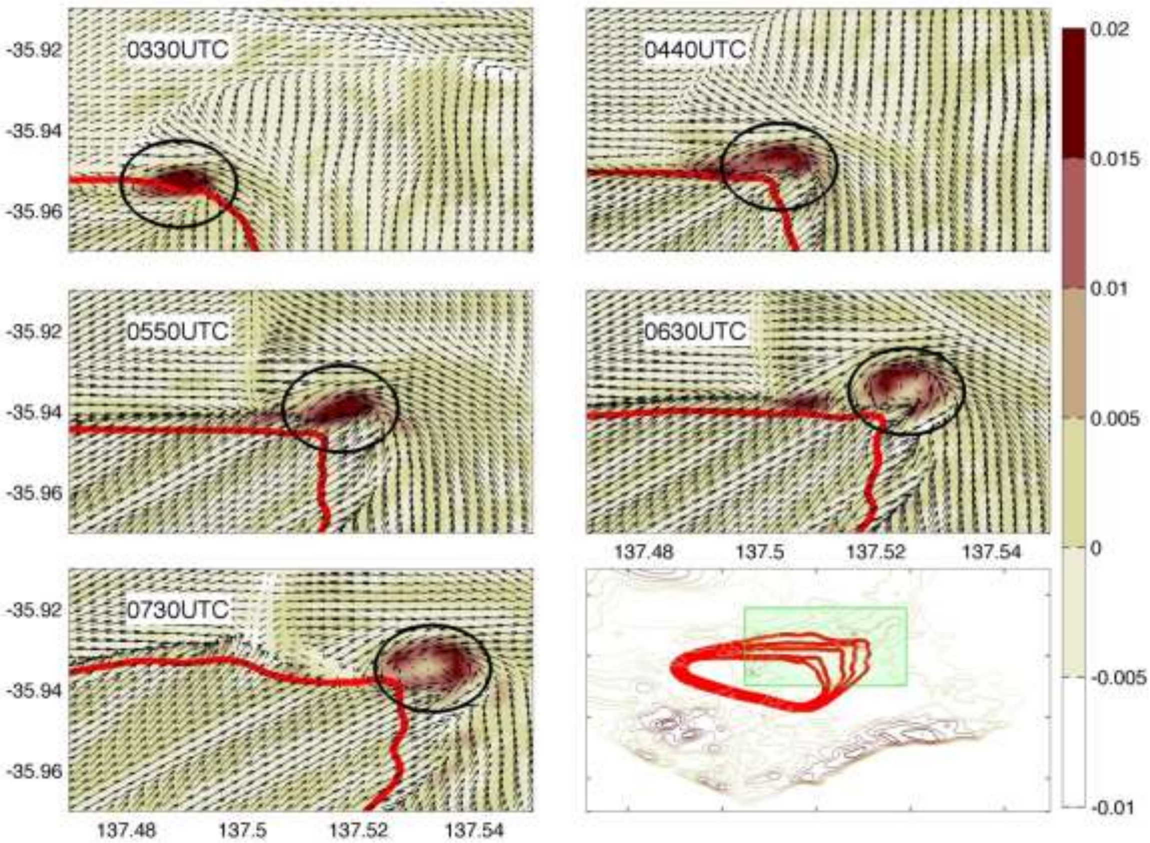

Figure 1. Wind vectors and vorticity (s^{-1}) (shaded, with vorticity about the vertical axis) at 10 m. Fire-line (feedback on) in red. Initialisation with ERA-interim meteorological grids. Lower right plot shows georeference and fire line reference for plots 1-5.

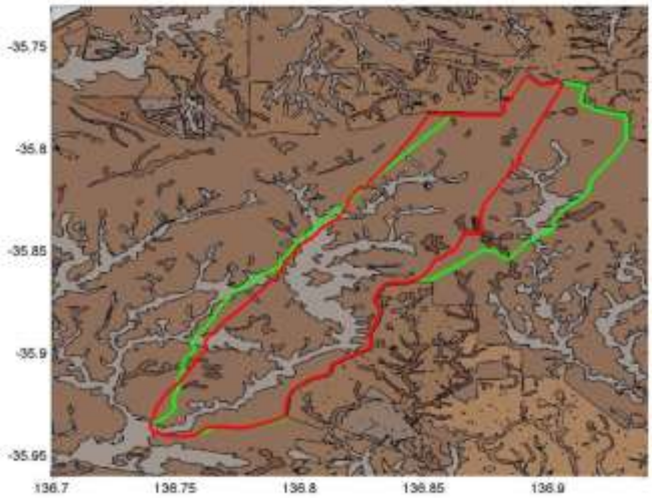

Figure 2. Simulated fire perimeter for the Rocky River fire at 1200UTC. Feedback on in red and feedback off in green. Shading shows fuel areas used in the model.

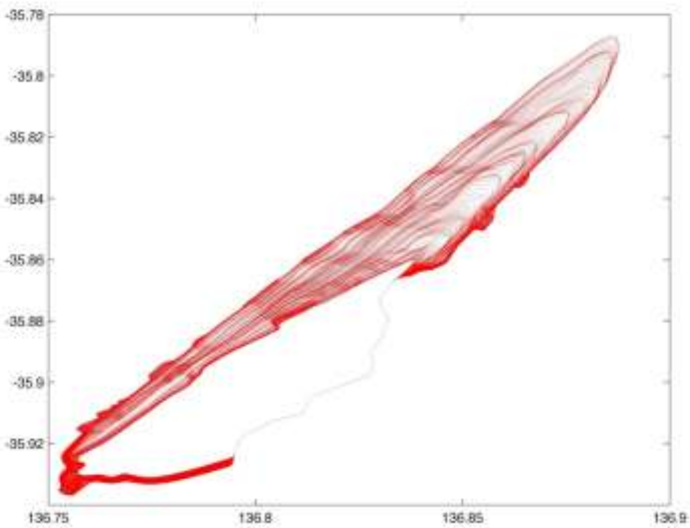

Figure 3. Fire isochrones for the Rocky River fire at one-minute intervals. Simulation from 0600UTC to 0830UTC.

Figure 3 shows fire isochrones for the Rocky River fire from output at one minute intervals for a period of 2.5 hours. During the period, winds were relatively steady across the domain in both speed and direction. In Fig. 3, surges or pulses in fire spread can be seen at the one minute interval outputs. These pulses are not associated with features of either fuel or topography. Rather, the timing of the pulses matched the passage of mesoscale convective cells at cloud height. This indicates that the surges arose from interactions between the fire and atmosphere.

3 CONCLUSIONS

The results from the coupled model show that interactions between a fire and the atmosphere can cause modification to the local winds that has consequent impacts on fire behaviour. In our simulations of the D'Estrees fire, coupling between the fire and atmosphere in the vicinity of a slow-moving front produced a large, long lived vortex adjacent to the head fire. The simulations of the Rocky River fire showed significant changes to fire spread and final fire area due to the fire- modified wind fields over topography. High temporal resolution simulations of the Rocky River fire showed a non-steady-state fire rate of spread in response to fire-atmosphere interactions.

Our results show that extreme fire behaviour may be attributed to interactions between the fire and the atmosphere. The simulations suggest mechanisms by which sudden increases in fire activity may occur and they show that wind driven fire spread at one minute intervals is not steady state due to fire-atmosphere inter- actions.

These results are thought provoking for the current approach to fire-weather forecasts and fire-behaviour predictions in Australia. Fire-weather forecasts focus on a near-surface point forecast of wind, temperature and relative humidity, following the McArthur framework. The simulation results, especially when considered in combination with case studies that examine the meteorology of unusual fire events, show that the three-dimensional structure of the atmosphere will influence how a fire behaves.

The scale of the feedbacks in the simulations shows the critical need for these elements to be incorporated into operational planning at fire events and strategic planning in the fire science community. Although the process of fire-atmosphere coupling and feedback behaviour remains poorly understood, it is essential information in order to mitigate against the impacts of bush fires and minimise risk during fuel-reduction burns.

Acknowledgements

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