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Commentary

Lessons Learned from Coupled Fire-Atmosphere Research and Implications for Operational Fire Prediction and Meteorological Products Provided by the Bureau of Meteorology to Australian Fire Agencies †

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† This discussion paper has been prepared for the BNHCRC 'Coupled fire-atmosphere modelling' project. It is intended for a primary audience of colleagues in the Bureau of Meteorology who have interest in fire related science and services, as well as stakeholders in land management and fire agencies.

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Abstract: Coupled fire-atmosphere models are simulators that integrate a fire component and an atmospheric component, with the objective of capturing interactions between the fire and atmosphere. As a fire releases energy in the combustion process, the surrounding atmosphere adjusts in response to the energy fluxes; coupled fire-atmosphere (CFA) models aim to resolve the processes through which these adjustments occur. Several CFA models have been developed internationally, mostly by meteorological institutions and primarily for use as a research tool. Research studies have provided valuable insights into some of the atmospheric processes surrounding a fire. The potential to run CFA models in real time is currently limited due to the intensive computational requirements. In addition, there is a need for systematic verification to establish their accuracy and the appropriate circumstances for their use. The Bureau of Meteorology (the Bureau) is responsible for providing relevant and accurate meteorological information to Australian fire agencies to inform decisions for the protection of life and property and to support hazard management activities. The inclusion of temporally and spatially detailed meteorological fields that adjust in response to the energy released by a fire is seen as a component in developing fire prediction systems that capture some of the most impactful fire and weather behavior. The Bureau's ten-year research and development plan includes a commitment to developing CFA models, with the objective of providing enhanced services to Australian fire agencies. This paper discusses the operational use of fire predictions and simulators, learnings from CFA models and potential future directions for the Bureau in using CFA models to support fire prediction activities.

Keywords: fire; meteorology coupled fire-atmosphere modeling

1. Executive Summary

This discussion paper was prepared as part of the BNHCRC (Bushfire and Natural Hazards Cooperative Research Centre) "coupled fire atmosphere modeling project". The key deliverables of the project were the development of the ACCESS-Fire (ACCESS is the Australian Community Climate and Earth-System Simulator) code that was written by Monash and Melbourne universities and the preparation of detailed case studies of two high impact fires. This discussion paper aims to capture the learnings on coupled fire-atmosphere modeling arising from project activities as well as learnings from operational deployments inside fire agencies during high-impact events.

In a changing climate, we are seeing increasing impacts from bushfires and demands for large scale hazard reduction burns, as well as increasing community expectations for information during natural hazard events. Accurate and timely fire predictions generated by simulation models are a key component towards meeting future information needs, and fire agencies are responding to this by expanding their cohort of fire behavior analysts. As the Bureau engages more strongly with fire agency partners to meet current and future needs, delivering relevant, complex meteorological numerical weather prediction capability and interpretation is vital. Coupled fire-atmosphere modeling has shown that some of the most impactful and unexpected fire behavior occurs as a consequence of fire atmosphere interactions. Therefore, future innovative services that appropriately capture the potential for extreme fire behavior are required to execute the Bureau strategy and to deliver impact and value to its customers.

This paper provides a summary of the main CFA models and highlights key contributions they have made to understanding fire and atmosphere interactions. The processes resolved by CFA models that are not captured in current surface-based predictions are particularly pertinent to Bureau capabilities in simulating atmospheric processes. We also describe current operational arrangements for fire weather products and services linking fire meteorologists, fire behavior analysts (FBAns), Australian digital forecast database (ADFD), incident weather forecasts (IWFs) and briefings, and suggest opportunities for enhanced services.

The final sections present a case for future needs of fire predictions and simulators and make recommendations for potential Bureau activities to meet these future needs. The favored long-term option is for collaborative development with CSIRO (Commonwealth Scientific and Industrial Research Organisation) and the Bureau of the Spark and ACCESS-Fire models as a pathway that would meet the operational imperatives of fast and flexible simulator capability in tandem with the capacity to run a more complex coupled simulator for research purposes and during extreme or challenging fires.

The preparation of this paper has involved consultation with fire and meteorology experts, a process that has highlighted the varying and sometimes conflicting viewpoints held by individuals in these traditionally separate scientific disciplines. Progress in developing a fire simulation capability that leverages the complexity of numerical weather prediction (NWP) and integrates fire fuel models to sufficiently capture dynamic feedback will require the collaboration of multiskilled and multidisciplinary teams.

2. Introduction

Fire prediction has become an important function in Australian fire and land management agencies as climatic and societal change create increased demand for informed planning and response to fire. Predictions of fire spread inform community preparedness and support emergency services response activities during bushfires. They are also a tool to manage risk and maximize effectiveness during hazard reduction burns. Australian fire regimes are being altered due to climate change through rising temperatures, earlier onset and later cessation of the fire seasons and changing frequency and intensity of extreme weather events (e.g., [1,2]). Consequently, there is an increasing demand for accurate, flexible and timely fire predictions with appropriate weather inputs that will meet information requirements for future events.

The main emphasis of fire prediction is on fire perimeter growth with time. It is a complex enterprise merging weather, fire behavior and topography as well as detailed information on fuel, including vegetation type, fuel moisture and time since fire. Fire predictions are prepared by specialized FBAns in fire and land management agencies. Across Australian jurisdictions, the methods and tools used by FBAns vary; some agencies focus on the production of hand-drawn maps while others use a range of fire simulation software. For both the hand-drawn and simulated predictions, the current approach to validation of results is not systematic.

The fire predictions made in Australia are generated using fire spread models applicable to individual fuel types. Australian fire behavior models are fuel type-specific across four major vegetation types: grassland, shrubland, dry and wet eucalypt forest and pine plantation. Ref. [3] describe 22 Australian fuel models that have been developed to predict the rate of spread for both wildfires and prescribed burning applications. The fire simulation models used operationally in fire agencies are software implementations of a set of the above fire spread models. It is likely that the current approach using manual predictions in some jurisdictions will be superseded by fire simulation models as technology progresses.

The requirements for an operational fire simulator are that it be flexible, portable and fast to run. It must include a range of fuel information, include response to topography and be compatible with geospatial datasets to facilitate display and interpretation. Data ingestion must be flexible, with easily editable layers. Simulation capability must be available to an Incident Management Team (IMT) that is located regionally; this is achieved either through simulations being run on-site at the IMT or on-demand at a central location. The required level of accuracy is that it be sufficiently accurate to be useful, which is considered to be within ~30% for the available fuel-specific models. The CFA models that have been used in fire meteorology research in Australia do not meet the operational needs described above.

Meteorological information is a key input to fire prediction. The fire simulation models and manual prediction methods currently in use ingest weather parameters of wind, temperature and humidity at the surface. The meteorological inputs are generally taken at a point in space and at hourly time increments and represent a limited subset of the complexity of information available in the surface and upper fields produced in NWP models.

CFA models have been shown to resolve some of the processes that contribute to the extreme behavior of very large fires that impact the weather around them; which supports the view that including detailed, dynamic meteorological fields in fire simulation models is a crucial component in building fire prediction systems that resolve some of the most impactful elements of fire behavior. The majority of CFA models currently in use, although appropriate for research purposes, do not present a clear pathway to meet future operational needs in Australia. It is likely that intermediate modeling solutions may be a better solution for meeting operational needs in short to medium term and be a suitable response to most fires in the longer term. Pathways for fully coupled CFA operational capability and the circumstances under which the approach provides high-value return can be established in the interim.

The fire activity that occurred during the 2019–2020 fire season sets expectations for future challenges facing the fire prediction enterprise. At times, the fires produced more rapid-fire spread than anticipated and extreme fire behavior developed on several occasions. The fire activity was attributed to extremely dry fuels contributing to high fire intensity, hot, dry, windy and unstable weather conditions, and fire-atmosphere interactions. The predictions produced by fire agencies using manual and simulator approaches under-predicted the severity of some of the high-end events.

The impacts of the 2019–2020 fire season illustrate the need for coordinated effort to set a clear research and development direction for the fire prediction modeling framework that will meet future requirements with sufficient flexibility, accuracy and timeliness to be useful.

As the Australian meteorological agency, the Bureau of Meteorology has a responsibility to provide relevant weather information to fire agencies for input to fire predictions. The Bureau's high-resolution numerical simulations have been used in contemporary fire and meteorology research to understand the processes that led to extreme fire behavior at several high impact events. CFA models have provided deeper insights through capturing the feedback between a fire and the surrounding atmosphere. However, the modeling approaches that best support research learnings and operational requirements may not necessarily be the same.

In this paper, we discuss how learnings from CFA models can improve fire-meteorology products and services through opportunities for training in the short term (1–2 years), how collaborative development of operational fire simulators can advance capability in the medium term (2–5 years) and what collaborative development may be required to run CFA simulators operationally in the long term (5–10 years).

- Short term: Increased training bridging the skills of FBAns, fire meteorologists, and embedded meteorologists will enable enhanced interpretation inside fire agencies and incident management teams via greater breadth and depth of knowledge of weather and fire behavior. The USA Incident Meteorologist (IMET) model provides a template for enhanced services.
- Medium-term: Collaborative development of operational fire simulators. The 2019–2020 fire season highlighted that coordinated national development of a single fire simulator presents the optimal pathway for interoperability. A collaborative approach will establish how to best include appropriate meteorological information. Weather ingredients may be included in the simulation framework or as complementary information embedded in the prediction process (e.g., red flags in the Australian fire danger rating system).
- Long term: CFA models currently present a long-term proposition but are yet to be proven for operations. Numerous transitional challenges for operational uptake exist, including; the mismatch of scale between NWP and fire prediction models; the effort required for systematic development and testing of CFA; inclusion of fuels and other GIS (Geographic Information System) data in current CFA; and how to meet operational timeliness and location requirements. Operational adoption would also require addressing the concern that CFA simulations implement fire spread models in a manner for which they were never designed.

This discussion paper captures learnings from the BNHCRC CFA modeling project. The project activities have spanned a greater depth and breadth than simply the development of ACCESS-Fire and case studies using the model. Consequently, the discussion draws on observations on how meteorological information and fire predictions are used in operations to suggest future pathways that will benefit the Australian community.

3. Fire Simulation Models Used in Operations

The fire simulation model used most widely in operations in Australia is Phoenix [4]. In WA, Aurora [5] is used. SABRE Fire (Simulation Analysis-based Risk Evaluation Fire), developed in Queensland Fire and Emergency Services, is used operationally in QLD. Spark, developed by CSIRO Data 61 [6], is not used operationally at present but has been developed with the intent for operational use. The Canadian model Prometheus has been trialed in some jurisdictions.

The various simulators implement fire spread equations for the dominant vegetation types across the landscape. In Australia, a unique fuel model is required for each vegetation type of interest. The new Australian Fire Danger Rating System (AFDRS; [7]) includes eight distinct vegetation types and empirical fuel models.

The vegetation (fuel) models have been derived through statistical methods from measurements taken during laboratory-based experiments or at controlled outdoors experimental fires supplemented by wildfire data (where available). This experimental approach is, to some extent, constrained by costs in terms of experiment design and data collection as well as limitations with respect to the feasibility of experimental projects. A strong advantage of the experimental approach is that it incorporates many of the elements that affect the spread and behavior of a real free-spreading fire burning under actual conditions. Some fuel-type models also output elements such as flame height and fireline intensity.

Fire spread models are highly sensitive to dead fuel moisture content, particularly at low fuel moisture when fire behavior increases non-linearly as fuel moisture decreases. In reality, fuel moisture can be highly variable across a fire area and due to measurement complexity, it is often estimated. The uncertainty associated with fuel moisture introduces a significant, known error to fire simulation output, which in many cases will be substantially greater than other modeling errors, such as sophistication in the landscape propagation algorithm or near-surface wind speed and direction.

The empirical fire spread models have been developed with the intent of supporting operational fire and land management decisions. Therefore, they use readily available data inputs to produce predictions. They meet the operational imperative of being sufficiently accurate and timely to provide guidance to support fuel management activities and to inform strategic and tactical decisions during bushfires. Operational fire simulators meet the requirements of expediency and portability. They produce the output of fire perimeter at the desired spatial resolutions of tens of meters and temporal resolutions of tens of minutes.

The Bureau of Meteorology fire model verification project [8] compared a set of operational fire simulators. The project team ran 10 different fire events on several different models and model versions. The verification results showed that all the fire prediction models assessed in the project displayed limited reliability and that the model error was non-systematic.

4. Categories of Fire Simulation Models

The set of three papers by Sullivan [9–11] provides a detailed summary of fire simulation and analog models used internationally at that time. Sullivan categorizes the models as physical and quasi-physical; empirical and quasi-empirical; and simulation and mathematical analogs. He states that many of the models have academic interest only, and he reiterates the point made in other publications; that some models have a role to play in understanding processes but may not be appropriate for operational fire prediction.

Following the categorization method of Sullivan, CFA models include both physical and empirical approaches. The physically-based models include equations that capture the physics and chemistry of combustion processes through conservation of mass, momentum and energy. Physical models have been used to address a range of research questions, but they are typically used to examine very small domains and are not considered appropriate for landscape-scale fires (e.g., [12]).

CFA models can also be categorized as empirical or quasi-empirical when they link an atmospheric modeling capability to a set of statistically derived fire spread equations. Such CFA models were first developed and run in the late 1990 s [13]; they capture interactions between the fire and surrounding atmosphere through interfacing an empirical fire prediction model with an atmospheric model. The coupling occurs by calculating sensible and latent heat fluxes released by the fire at each time step, dependent on the distance the fire front has spread and the amount of fuel consumed. These energy fluxes are passed to the atmospheric model, which subsequently alters the temperature and humidity and the structure of the winds and thereby completes the coupling.

The atmospheric response is most apparent as the wind fields produce convergent flow towards the fire front, a phenomenon which is known as fire-modified winds. The fire-induced wind response in CFA simulations may vary in speed and direction from the environmental winds for distances several kilometers away from the fire-front.

The atmospheric component of a CFA model takes one of two types. They are either CFD (computational fluid dynamics) models or numerical weather prediction (NWP) models. CFD models (e.g., HIGRAD) are designed to resolve small scale fluid flows (particularly turbulent processes), and this makes them useful for examining the detail of flow surrounding a fire. They can also resolve the spatial scales of combustion processes, vegetation structure and small-scale eddies. However, a consequence of their small grid spacing is that domain size is restricted in accordance with computational requirements, and they are not suitable for simulating fires at a landscape scale.

NWP systems implemented through CFA modeling approaches include the ACCESS model [14]; configured with a sequence of nests at increasing resolution to achieve a scale suitable for resolving fire processes; the WRF model [15], which requires initial and boundary conditions from a global NWP model, but has the advantage of comparatively flexible configuration at high-resolutions, and the CAWFE (Coupled Atmosphere-Wildland Fire Environment) model [16], a convective scale model which is similarly initialized from a global model, but tailored to capture convective processes.

5. Use of CFA Models

The main ingredients driving fire behavior are available fuel, weather conditions and terrain, and the interactions between these elements can drive extreme fire behavior (e.g., [17]). The terrain is static while fuel availability changes over a range of time frames (fine fuel moisture over periods of hours, with longer changes in response to seasonal and decadal rainfall) as well as antecedent fire activity. Meteorological processes are the short-term dynamic factor driving extreme fire behavior. Under certain situations, elements of fire behavior such as high flame height, anomalous propagation direction in prevailing winds, fire-induced vortices, organized, convective plumes and deep pyro-convective cloud development and spotting may occur.

Because observations are difficult to collect in a fire environment, CFA models are a valuable tool for understanding the processes surrounding a landscape-size fire. An important contribution from CFA models is the understanding of the modification of wind fields surrounding a fire. This includes mechanisms such as the causes for rapid downslope spread; demonstration of how the ellipse shape of fires forms through convergence along the flanks; understanding downslope winds and associated turbulence; and momentum entrainment of above-surface winds that can accelerate the spread of the head fire.

CFA models can also provide information on the trajectory and injection height of particles. This is useful for understanding and predicting smoke dispersion and smoke trajectories. Plume dispersion models (e.g., HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory model) [18] provide trajectory information but rely on assumptions of particle injection height, a process that can be directly resolved using CFA models.

6. The Physical and Empirical Coupled Models

WRF-Fire was first described by [19]. It comprises the Weather and Research Forecasting model (WRF) [15], which has been used internationally to address a range of meteorological questions, linked through a level set spread algorithm to the Rothermel fire spread model [20], which uses the Anderson fuel system [21]. The development of WRF-Fire and the WRF-SFire model diverged from 2011. Reference [22] described the WRF-Fire model, which is the first CFA model to be used operationally, in combination with CAWFE, in the Colorado trial (see later section). WRF-SFIRE has been used for post-event analysis of several landscape-scale fires in a variety of environments around the world including [23] and [24] as well as idealized simulations [25]. WRF-SFIRE has been integrated with WRF-CHEM to combine fire spread, smoke production and smoke dispersion in simulations and a coupled fuel moisture model.

ACCESS-Fire has been developed in Australia and links ACCESS to an empirical fire model. It was developed to study the Black Saturday Kilmore East fire [26], and work with the model has continued through a bushfire and natural hazards CRC project. The fire model interacts with the atmospheric model via sensible heat and latent heat fluxes passed through the land-surface scheme. The following fire behavior models are included: McArthur forest and grass, CSIRO grass and forest and Rothermel. Conclusions from simulations of the Black Saturday Kilmore East bushfire included: accuracy of the simulations was attributed to fire-atmosphere coupling processes; incremental gains in accuracy were achieved by increasing horizontal resolution from 300 m to 100 m, and including locations of spot fire ignitions from the fire reconstruction was integral to simulation accuracy.

CAWFE stems from the work of [13]. The research with CAWFE is (almost) exclusively by Janice Coen, who has published several seminal findings on the contributions of coupled modeling to understanding of fire-atmosphere interaction processes. Coen states that a key advantage of coupled NWP models is that they capture wind effects, which are arguably the most important component in landscape-scale fires. She asserts that the CAWFE framework is best suited to capture the important small-scale flows and fire interactions with topography.

FIRETEC/HIGRAD high-resolution model for strong gradient applications (HIGRAD) is a three-dimensional hydrodynamics model, and FIRETEC is the fire component. The governing equations are based on averaging of conservation equations for mass, momentum, energy and chemical species. A number of empirical models for resolving combustion and burning processes are included. HIGRAD is appropriate for limited spatial domains as it runs at horizontal resolutions of 2–10 m on a finite volume grid. FIRETEC/HIGRAD development is led by Rod Linn, who describes physically-based models as learning tools not suitable for operations. FIRETEC is primarily used at the Los Alamos National Laboratory and is applied to research questions that depend on resolving turbulent-scale variability in atmospheric quantities. FIRETEC has been used in "what-if" scenarios to assess potential fire damage to sensitive locations at sites in fire-prone ecosystems.

WFDS WUI is the wildland-urban interface, and FDS the fire dynamics simulator component of WFDS [27]. WFDS is based on approximations to the governing equations of fluid dynamics (the Navier–Stokes equations), combustion and thermal degradation of solid surface fuels. It is described as useful for examining some of the processes not amenable to field experiments and not resolved by empirical or semi-empirical models. It captures the fire response to ambient winds, atmospheric stability, vertical wind structure, plume dynamics and buoyancy. It is not intended as a landscape model. WFDS has been used to study laboratory burns in wind tunnels and the potential for structure fires in the wildland-urban interface with an emphasis on heat, ember and smoke transport.

Meso-NH and ForeFire [28] have been developed in France using Meso-NH, which is the non-hydrostatic mesoscale atmospheric model used by the French meteorological research community. Meso-NH is run in LES (large eddy simulation) configuration with ForeFire, a physical fire rate of spread model.

The various coupled modeling frameworks described above have primarily been applied to research questions, not an operational application, and they and capture different aspects and scales of meteorology and fire behavior. A benefit of NWP linked CFA models is that they capture the wind fields at landscape size fires. CFA models are not presently considered to be sufficiently mature for operational use in Australia due to their computational complexity and because they have not undergone rigorous testing and validation.

7. USA Perspective and the Colorado CO-FPS

This section describes the research and use of CFA models in the USA and has been contributed by Joseph Charney.

Research culture in the USA has encouraged the development and use of numerous, diverse CFA model frameworks, driven by a need to support a broad spectrum of potential applications in research and operational settings. The range of coupled models developed over the last two decades results from the philosophy that more models are better, and each contributes uniquely to the complex set of research and operational issues surrounding fire and meteorology. The WRF-Fire, FIRETEC, and WFDS coupled models are being used to investigate fire-atmosphere and fire-fluid-dynamical interactions across scales ranging from laboratory wind tunnels to large fire complexes.

The Colorado fire prediction system (CO-FPS), which consists of a combination of the CAWFE and WRF-Fire models, is undergoing focused development to produce a tool applicable to operational, real time, fire spread prediction. CO-FPS developers have established that two-way coupling, particularly in complex terrain, is important for effectively simulating fire spread on time scales of 6–12 h. Additionally, CO-FPS investigations suggest that coupled model accuracy declines sharply for predictions longer than 12–24 h; they conclude that operational fire spread prediction using current models is best pursued in a "rapid-refresh" data-assimilation mode. This finding is not exclusive to CO-FPS but holds for all fire models. The technique employed is to predict meteorological conditions and fire spread for the next 12–24 h, then restart the simulations with updated information on fire perimeter, meteorological observations, and new forecast runs. This approach currently shows the most potential for improving real-time prediction of fire spread in complex terrain. The WRF-Fire prediction system is just one component of the overall decision support project, which also includes ground and aviation response to fires.

The National Institute of Standards and Technology in the USA, who originally developed the WFDS model, is laying the groundwork for a single CFA modeling system that can be applied across a range of spatial and temporal scales. The philosophy underlying this effort is that a CFA framework must be designed to take advantage of the anticipated increase in computing power in the coming years. Specifically, the model must scale effectively in massively parallel supercomputing environments. This will enable the underlying physics of the model to be tested with available laboratory and field observations, and the resulting model refinements will immediately become available for landscape-scale applications in an ensemble model. The time scale for this development is not yet clearly established, but the prototypes of the system could appear in the next five years.

The comparatively large size of the USA research community supports diverse research streams, while the scale of resources in Australia is more limited. Development of coupled models in the USA has partly been accelerated through unrestricted sharing of source code, thereby increasing the user-base.

8. Fire Simulators for Operations

8.1. Research to Operations

In Australia, the use of CFA models to date has generally been to investigate research questions that aim to further understand fire and atmosphere processes. The underpinning objective has been to establish the appropriate inputs and use of meteorological information in order to inform the fire prediction techniques and operational simulators that best capture fire behavior.

8.2. Fire prediction Applications

Fire predictions inform two real-time requirements; wildfires and hazard reduction burns. Fire predictions are also used on longer time scales for risk-assessment. Typical outputs include fire perimeter maps, rate of spread estimates, heat output or fireline intensity, flame height, transition to crown fire and spotting potential. Probability information is appropriate for many of these elements.

Using wildfire predictions, information on fire perimeter at specific time intervals and assessments of the potential for extreme fire behavior are used to support risk assessment and mitigation decisions, including evacuations and deployment of suppression and other resources, as well as the assessment of firefighter safety. Threat mitigation is a critical concern. The temporal requirement for predictions ranges from minutes to days, with spatial requirements capturing a wide range of fire sizes from post-ignition to 100,000+ ha.

For planning and managing prescribed burns, the focus is on identifying windows of opportunity for effective burns and optimal ignition patterns. Simulation results are used to anticipate likely fire behavior, particularly for assessing potential risks, including the possibility of escape. Lead times are longer than for wildfires and are typically hours to days. Spatial requirements range from fires of one to thousands of hectares, up to ~10,000 ha. Fire predictions that support risk assessment and planning will be required to have increased accuracy as the urban-rural fringe expands and climate change shortens the seasonal window for favorable conditions.

Some fire agencies also run multiple scenarios to produce risk profiles across an area. Ignition likelihood is a component of such assessments. For scenario simulations, the model framework must be similar to that used in operations in order to support valid comparisons. Simulation time is not imperative for these applications.

9. Operational Data and Information Requirements

During a bushfire, information complexity must balance timeliness and accuracy requirements. Delays incurred waiting for simulation results or slow functionality while interrogating data may have flow-on consequences for the protection of life and property. The current suite of operational fire prediction simulators run quickly on personal computers. As CFA models develop, information on execution time and computational resource requirements need to be measured and shared.

Operational decisions need to be informed by the skilled interpretation of robust science, using information that is viewed on an integrated, flexible platform. The same platform should be used for meteorological, fire and other geospatial data. Predictions for both meteorological parameters and fire spread should be easily verified in real time. A feature of both the Spark and Phoenix simulators is a design platform that enables viewing of high-resolution GIS datasets, including roads, infrastructure, fuel maps, and linescan imagery.

In the USA, investment has been made to display complementary spatial datasets on integrated platforms. At present, the spatial and temporally varying meteorological fields from the Bureau's Australian digital forecast database (ADFD) are incompatible with the operational GIS-based platforms used by fire agencies. Different data viewing platforms are used by meteorologists and fire behavior analysts (FBAns), which makes an objective comparison of relevant fields challenging. This in part due to the mismatch in resolution between the primary spatial scales for fire and meteorology. This applies to both coupled and uncoupled simulations and is a serious operational constraint that should be addressed to optimize the fire prediction enterprise.

The ability to view relevant fields simultaneously on a single, coherent platform with sophisticated mapping tools is imperative, particularly in time-critical situations. Available and emerging technologies that should be included on an integrated platform include drone images, linescan images, suppression activities, satellite imagery at 2.5 to 10 min refresh rate, satellite-derived fuel moisture, grass curing and related metrics, national fuel grids and fuel age when available, AFDRS data fields, radar and lightning data, soil moisture in multiple layers, recent rainfall at varying time periods, infrastructure including roads and firebreaks and topographic data sets.

Real-time availability of data is often limited; however, rather than limited data being perceived as an issue to be addressed by increasing data quantities, it highlights the importance of skilled interpretation to inform decisions.

As fire prediction systems become more widely used and more complex, deep knowledge to interpret the results and effectively communicate messages will be required. This will require meteorologists and FBAns to stretch across traditionally separate disciplines, with the optimal outcome likely to be multidisciplinary teams. Output products and displays produced by these teams must be tailored to be fit for purpose for both specialist and community audiences.

Ensembles

The use of ensembles is rapidly expanding in numerical weather prediction, with operational ensembles released in Australia in 2020. Some fire simulators produce limited ensemble output (e.g., SABRE, used in Queensland by QFES). Ensemble fire predictions present a complex challenge because the appropriate methodology for choosing an appropriate range of starting conditions for a fire simulator is not clear. Using a meteorological ensemble is one option. However, in many cases, the range of uncertainty in the meteorological inputs is substantially lower than the uncertainty and spatial variability in other inputs, such as fuel moisture or the likelihood of fire spread across a barrier such as a river or a road. One value proposition for the use of fire simulation ensembles initialized by meteorological ensembles is information on the likely timing and strength of a sea breeze or frontal wind change and the possible fire spread in response.

10. The Current Operational Activities Linking Meteorologists and FBAns

This section captures operational experiences of fire agencies during the recent fire seasons. It provides context for how CFA models would interface with real-time operations. Particular emphasis is placed on embedding existing learning against investment in CFA operationally.

The meteorological information provided by the Bureau to fire agencies as input to fire predictions (for going fires or hazard reduction burns, not fire danger ratings) takes two main forms: "incident weather" forecasts prepared by meteorologists and data extracted directly from the ADFD. These are sometimes, but not always, complemented by verbal briefings by meteorologists.

Forecasts and briefings are provided by qualified meteorologists, severe weather forecasters or "embedded meteorologists" who have a high level of meteorological training and meet established fire weather competency requirements. However, knowledge of fire science and emergency services procedures is highly variable across individuals in the national team of meteorologists who provide services to the fire agencies. The fire-weather training provided to meteorologists remains strongly embedded in the McArthur framework, and the operational verification focus is on near-surface conditions of wind, temperature and relative humidity.

In NSW RFS during the 2019–2020 fire season, there was a continuous requirement from the team of up to 12 FBAns in the state operations center (SOC) and from regional IMTs for the embedded meteorologists to provide additional information to supplement the IWF's and ADFD grids. This constituted a significant component of the workload of embedded meteorologists in RFS. Requests included: "checking" ADFD grids for "accuracy" and providing greater spatial information that reflected variable conditions along firelines that frequently extended across several ADFD grid points; discussion on potential convection column development, feedback processes and plume trajectories; potential for overnight influences, especially winds mixing down from above the surface and the depth, likely onset and break timing of nocturnal inversions; variability in winds and inversion structure across terrain features of peaks and valleys; precipitation type and timing (for example whether brief showers were expected or extended periods of drizzle with reduced visibility, information which is not captured in ADFD, but critical to backburning operations); and smoke trajectory information (particularly for smoke recirculating over several days, which is not captured in the point source AQFX tool).

During peak demand, 20–30 IWFs were prepared each day, and these were prepared by meteorologists in NSW and nationally who had a range of experience. This experience range was reflected in the level of detail and interpretation captured in individual forecasts. Several IMETs on exchange from the USA were noted for preparing the most detailed and interpretive IWF's, demonstrating the value of their training in fire behavior and their experience on fire grounds.

There is an open and immediate opportunity to develop skills in a group of "fire-meteorology specialists" in Australia. The USA incident meteorologist (IMET) program provides a template for the capability. In addition to meteorological expertise, the fire meteorology specialists would have extensive training in fire behavior that may include: fire agency and land management needs, pressures and activities; fuel types, burn prescriptions, knowledge of fire simulation models, their inputs and sensitivities and limitations; and learnings from case studies of unusual events and findings from coupled fire-atmosphere models. Incident management training would be a key component, ideally following the Australasian inter-service incident management system (AIIMS) approach favored by agencies. Development of a capability set would intersect skills and training of FBAns, with the objective of creating complementary expertise in high-functioning teams.

Some of the learnings from coupled modeling include fire-atmosphere interactions such as processes surrounding downslope winds, convection potential and downdraft processes near fires, interaction with boundary layer meteorological features including convective cells and boundary layer rolls, wind convergence along ridgelines, modification of frontal lines near fires, assessment of plume depth and organization, likely spotting potential and direction and anomalous propagation direction driven by turbulent processes such as vorticity driven lateral spread.

Ingredients-based tools could be developed to identify risk areas with potential for extreme fire behavior, and fire-meteorology specialists would receive focused training to develop expertise in recognizing favorable environments for unusual fire activity.

The pathway of meteorology–fire experts complements the increasing numbers of FBAns in all states and has the potential for adding value in risk management and impact mitigation during both significant fire events and in planning for prescribed burns.

11. Requirements of a Future Fire Simulation Model

The elements described in this section are desired components of a robust and accurate operational fire prediction system. They are generally applicable to both coupled and uncoupled frameworks. Development of tools that enhance the predictive capability of the elements listed below may provide a comparable or greater return (in terms of mitigating impacts) than investment in CFA models.

11.1. Deep Convection in Coupled Models

The skill of coupled fire-atmosphere models in resolving processes above the boundary layer, particularly cloud development, extent and depth, has not been systematically examined and documented. Deep convection leading to towering pyrocumulus and pyrocumulonimbus is a question of intense meteorological interest, although the relationship between pyrocumulonimbus and surface fire behavior has not yet been systematically correlated. ACCESS-Fire has resolved cloud processes consistent with pyrocumulonimbus; however, verification of cloud depth and location against observations was not performed.

Convective clouds can produce convective downbursts that may alter the fire front direction and rate of spread. However, due to the localized nature and inherent uncertainties of the convection process, it is likely that a probabilistic rather than deterministic modeling approach is appropriate to inform operational decisions on potential impacts from convective outflow boundaries. The pyrocumulonimbus firepower threshold or PFT tool [29] has been informally trialed in operations during the 2019–2020 fire season. It shows a useful skill for predicting pyrocumulonimbus or towering pyrocumulus cloud and therefore shows that useful operational guidance on deep moist convection can be provided without requiring the full complexity of a CFA model.

11.2. Spotting

Spotting is a key element of fire spread, particularly in Australian eucalypt fuels. Case studies and fire reconstructions have shown that observed fire spread in landscape-scale fires frequently cannot be re-created or predicted without including downstream ignitions from spot fires. However, spotting should only be incorporated in predictions as a stochastic process. Simulation approaches that include information on plume injection height, updraft velocities, average and maximum burnout time, turbulence and transport wind speed will best resolve the spotting process. CFA models provide some of this information, but useful operational predictions may be achieved through less computationally intensive approaches e.g., [30].

11.3. Verification, Data Assimilation and Rapid Update

Continuous verification in NWP models over a period of several decades has informed improvements that have been instrumental in achieving the current accuracy of weather predictions. The verification approach to fire spread predictions is not analogous. This is in part due to the difficulties in the continuous, systematic collection of observational data for verification, as well as the fact that firefighting activities and fire suppression and mitigation efforts alter the fire progression so that the potential for unrestricted fire spread often does not occur.

Verification of fire predictions is also challenging due to uncertainties such as fire crossing barriers such as roads or rivers, which may be attributed to the impacts of a single tree or ember.

Data to support more systematic verification will result in improvements to both coupled and uncoupled fire simulations. Comparison of coupled and uncoupled predictions with the objective of assessing the circumstances under which coupled approaches deliver maximum benefit would be useful in assessing the future contribution of CFA models.

11.4. Data Assimilation

Operational fire simulations must include a range of information at appropriate temporal and spatial scales, including accurate ignition time and location, geospatial data including fuel information (type, quantity, time since fire) and disruption information such as roads, water, breaks and burned-out areas.

In both meteorology and fire simulation, real-time data assimilation and rapid update cycles have been shown to produce the most accurate predictions to support operations. It is possible that greater investment in data capturing and rapid update cycles will deliver comparable or greater return on investment than CFA modeling. Data capturing and rapid updating will become more feasible in the future as remote high-resolution observation capabilities such as drones become more accessible. Design of modeling capability that continuously updates to include complex information on impacts and suppression will benefit operations.

11.5. Fuel Moisture

Fire spread and intensity are highly sensitive to fine fuel moisture. Fine fuel moisture varies considerably in time and space with changes in topography, aspect and diurnal processes. As fuel moisture lowers, fire behavior increases non-linearly in response. Consequently, fine fuel moisture is one of the most sensitive inputs to fire spread models and the most difficult input for which to obtain accurate landscape-scale data. Accurately assessing landscape-scale fuel dryness, particularly at the high end of the scale due to compounding influences of drought, low rainfall, and heatwaves, was a challenge during the 2019–2020 fire season.

11.6. Scalability

A highly scalable approach to fire prediction is required to adjust for fire size across the spatial scales of large landscape fires and hazard reduction burns. ACCESS-C guidance currently provides the best available initial meteorological conditions at hourly (or potentially sub-hourly) time steps. The operational atmospheric grids of 1.5 km can be downscaled to 400–100 m, which is an appropriate spatial scale for the simulation of landscape-scale fires. Sensitivity tests run with both ACCESS-Fire [26] and CAWFE [31] showed limited improvement in CFA simulation results when the resolution on the inner nest was varied from 400 m to 100 m.

12. Options for Future Operational Fire Simulators

The Colorado CO-FPS project demonstrates that CFA models can be run operationally. There is potential for operational use of CFA models in Australia, particularly as computing capability increases and research efforts resolve current barriers. However, the pathway and timeline are uncertain, and the case is not clear that operational CFA models present the optimal solution to meet operational fire prediction needs in Australia, recognizing that those needs, and the technological capabilities to meet them, will continue to evolve in the future. The use of CFA models in Australia has thus far been in individual small research projects. Future applications and development of CFA models should be informed by and occur alongside the roadmap for fire predictive services, the draft of which flags inclusion of coupled models in the operational suite within ten years.

The following section discusses three potential pathways that may be pursued by the Bureau and its fire agency partners. Two pathways are for fully coupled operational models, and the third is for collaborative development of the CSIRO Spark model to include some of the processes captured in CFA models.

12.1. WRF-Fire

The operational development of WRF-Fire in the USA is well advanced, and therefore it presents an accelerated pathway towards implementation in Australia, with the benefit of cross-continental collaboration to accelerate progress. The model includes a smoke and chemical transport scheme. The code currently implements the Rothermel fire model, but it is conceptually and technically uncomplicated to substitute algorithms for the eight fuel categories contained in the new AFDRS. WRF-Fire could be initialized with deterministic or ensemble hourly 1.5 km ACCESS-C/(CE3) grids. A perceived disadvantage of using WRF-Fire is the divergence from the established commitment to ACCESS as the primary model for Australian research and operational systems. An advantage of WRF is easy scalability to adjust domain and fire sizes, and it has been run and tested on real and idealized simulations and used in research and operational applications. A reasonable time estimate for implementation would be relatively short (a few years).

12.2. ACCESS-Fire

Implementing ACCESS-Fire operationally is not feasible in the short term. However, it presents a viable longer-term pathway, subject to extensive further development and testing. A constraint in research simulations has been that the overarching unified model (UM) structure and dynamic core of ACCESS were not developed with the intent of performing high-resolution simulations with large energy fluxes driving strong vertical and horizontal accelerations (e.g., the lower limit timestep of one second is a restriction to model stability). However, we believe this issue has now been resolved.

Australia has made a long-term commitment to ACCESS and partnership with the UK Met Office, so the development of the CFA capability is consistent with national and international objectives. The UM code is undergoing a substantial rewrite in response to changes in computing structure, so current numerical stability challenges may not continue with the future model configuration. Operational plans for ACCESS include relocatable high-resolution nests to examine the detail of high impact weather events, city-scale forecasts, data assimilation of Mesonet observations and particle transport for agricultural and biohazard applications. These objectives are complementary to and could occur in parallel with the development of ACCESS-Fire. Additional advantages of plugging into the ACCESS ecosystem include enhanced functionality for data assimilation, ensembles, and the land surface scheme.

The Kilmore East Black Saturday simulations [26] and simulations in the progress of the Waroona and Sir Ivan fires show the potential value of the system. Numerous development steps would be required for operational use, including the inclusion of fuel grids compatible with the AFDRS, variable fuel moisture and the inclusion of smoke transport. Smoke transport could be implemented in collaboration with air quality work at CSIRO.

12.3. Other Considerations in CFA Models

Differing viewpoints have been expressed regarding the role of CFA models. One view questions the desire to use high fidelity NWP models through creating simple interfaces with existing empirical fire spread models, a purpose for which neither model framework was designed and an approach for which fire spread models are not defined. The other view sees that a singular commitment to two-dimensional empirical models as operational prediction tools will be deficient during major events when large fires burning in extreme conditions will produce dynamic fire behavior through complex interactions and that using a more powerful computing framework will provide an improved solution. The optimal operational solution is likely to be a compromise of both viewpoints.

CFA models are unlikely to add value in all situations. Fires burning in heavy fuels in complex terrain and conditionally unstable atmospheres with deep boundary layers are most favorable for exhibiting dynamic fire behavior. The situations when CFA models are most likely to deliver value will become more apparent as more testing occurs.

12.4. Spark with Flags to CFA Learnings

The prediction system that best meets the future operational requirements of accuracy, flexibility, portability and expediency may be optimally achieved through a blend of coupled and uncoupled approaches.

Such a system would not be as complex or computationally expensive as a fully coupled model. The potential framework would incorporate a two-dimensional fire simulator with a set of components to capture important elements from the coupling process.

The coupling components may include a set of ingredients-based algorithms that identify meteorological environments favorable for dynamic or extreme fire behavior.

Spark is the most promising of the currently available bushfire simulators due to its national approach and modular interface, which provides a framework to include meteorological ingredients at an appropriate level of detail.

Development of Spark and ACCESS-Fire in parallel is consistent with the data sharing emphasis of the Royal Commission during 2020 and presents a balance between the desire for CFA operational capability and real-time information demands and computational availability. A flexible future-focused design would leverage off planned advances in high-resolution NWP and High-performance computing, and machine learning.

This case would require broad discussion, wide expertise and careful consideration of key inputs. It may be the best approach long term, particularly in view of the recently announced 10-year National Research Center for Disaster Resilience, and robust discussion on this avenue would be worthwhile.

13. Summary and Recommendations

Bushfires and their impacts in Australia are expected to increase due to climate change and due to increased numbers of people living at the urban-rural interface. These factors, as well as raising community expectations for information during natural disasters, will present an increased demand for the relevant and accurate fire weather information provided by the Bureau of Meteorology to fire agencies. A new generation of fire simulators will be required to meet future demands for informed risk management and mitigation response decisions.

Experience during the 2019–2020 fire season showed that neither ADFD grids nor point forecast Incident Weather Forecasts fully met the information requirements of the FBAns who produce fire predictions for IMTs and SOCs. More complex and detailed dimensional, spatial and temporal information is required to produce accurate predictions and effectively communicate the risk of potential fire behavior.

CFA models are a capability that captures some of the most impactful fire behavior by resolving the complex interactions between a fire and the surrounding atmosphere. CFA models are in the early stages of development and use in Australia; results from simulations have shown their value in understanding interactions and resolving some of the above-surface meteorological processes that drive fire behavior.

ACCESS-Fire is a CFA model that has been developed in a research capacity in Australia. The ACCESS application links seamlessly to Australian research and operational weather and climate prediction systems. However, the ACCESS-Fire framework does not presently meet requirements for operational fire prediction as the research version is not sufficiently flexible or fast to run. There is currently no pathway to use ACCESS-Fire operationally, and a future configuration similar to that used at present would not be favorable for running simulations on dozens or more individual fires in a day.

Fire simulators that leverage information from high-resolution NWP will be required to meet future fire prediction requirements. The optimal long-term development pathway may be parallel development of ACCESS-Fire and Spark, with some shared code components and parameterizations. This would produce a future capability where Spark would be run routinely on most fires, with a mechanism or flag for identification of environments or fires where the assumptions in Spark would provide limited guidance and therefore running a fully coupled model at significantly greater computational expense would be of value.

Advances in fire-meteorology operations and research have been achieved through forward-thinking, collaborative partnerships between fire and meteorology researchers and fire practitioners. The AFDRS is an example of a successful partnership, and the verification project is another. A similarly collaborative approach is required to develop the next generation of fire simulators that implement fire spread models for Australian fuels.

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