Research Statement

My research is in the discipline of wildfire (bushfire) science, an interdisciplinary field that has developed considerably over the past 30 years. The field encompasses work by ecologists and foresters, climate scientists, remote sensing scientists, meteorologists, social scientists, physicists, engineers, and mathematicians. The overarching goal is to better predict the ignition, spread, and impact of wildfires so that the risk of wildfire can be managed.

Specifically my research is focused on developing physics-based simulation techniques, investigating physical processes that occur during wildfires, and using those results to inform the development of reduced models of wildfire phenomena that can be used by operational managers and emergency services.

The impact of wildfires in Australia is devastating. The recent Black Summer fires of 2019-2020 directly claimed 34 lives, and indirectly 445 lives associated with smoke inhalation. An estimated one to three billion animals (terrestrial vertebrates) died. The economic costs are tentatively estimated at AU$100 billion[1]. The Black Saturday Fires in Victoria in 2009 directly claimed 173 lives and caused an estimated AU$4.5 Billion in a single afternoon. Wildfire disasters of similar magnitudes in terms of fatalities and property losses occur world wide, particularly in North America and Europe.

Given the importance of the impact of bushfire on Australia, there is great funding potential for wildfire research. Currently I am a chief investigator on two ARC Discovery projects (DP210101965, DP210102540). The first project examines the behavior of smoke transport by gravity currents, such as inundated Canberra during December 2019 and January 2020, directly causing one death and significant economic disruption, using numerical simulation with an eye to developing better estimates of smoke concentration in such events. The second project seeks to combine field experimental fire measurements with physics-based modelling to develop computationally efficient models to better predict the rate-of-spread and intensity of merging and coalescing fires; a process that leads to some of the most devastating extreme fire behaviour. There are numerous other funding opportunities through Natural Hazards Australia (the organisation that replaced the Bushfire and Natural Hazards Cooperative Research Centre), state government recovery funding and the opportunity for ARC Linkage projects with Emergency services agencies and organisations such as The Suburban Land Agency in the Australian Capital Territory. There is also potential to work with the insurance industry, whose core business is significantly impacted by wildfires, power and water utilities whose infrastructure may be impacted by wildfires, and Defence partners who are interested in wildfire impact on their bases and more broadly wildfire as potential a national security issue.

My research uses computational fluid dynamics (CFD) simulations to better understand the processes that occur during wildfire. Much of my work has used physics-based simulation techniques[2]. In wildfire science the term physics-based simulation is used to distinguish simulation methods that attempt to represent all physical processes, particularly combustion, as faithfully as possible, from other simulation techniques which ignore combustion and parameterise fire spread as a hot region that spreads at a predetermined rate. Current fire spread models used operationally use some numerical technique, such as the level-set equations[2], to advance a fire contour at a rate determined from empirical-derived statistical models. Importantly, the models that are used operationally in Australia do not consider the action of the fire plume upon the atmosphere. Intermediate simulation techniques that capture the effect of the plume on the surrounding wind fields are called coupled-fire atmosphere models. They use a numerical weather prediction model with the fire represented as a surface temperature perturbation moving with predetermined rate. Physics-based models include combustion, but due to the short length scales associated with combustion and radiative heat transfer to the fuel bed, the number of discretisation points is very high. The size of fires that can be simulated using physics based models is limited to regions of the order of 100 m $\times$100 m[4].

My previous and current work focuses on using physics-based simulations of grass fires to validate the physics-based simulations by comparing simulations to available experimental data and then to investigate the sensitivity of fire spread to different parameters such as fuel moisture content. I am also interested in investigating the effects of different fire geometries and configurations upon the rate of spread of the fire. A PhD student (that I co-supervise with Prof. Moinuddin) at Victoria University has used physics-based simulation to investigate the behaviour of wind-driven fires propagating up and down sloped terrain. I have used physics-based simulations to investigate different ignition protocols used in various field experiments throughout Australia. The key finding of this study is that the ignition technique has significant influence on the development of fire spread and the previously held assumption that the fire quickly obtains a constant spread rate is not valid. Currently, I am investigating the behavior of merging fire lines using physics based models as part of the ARC discovery project on megafires. When two straight line fires merge in a v-shape the apex of the fire spreads at a significantly increased rate (more so than can be explained by geometrical considerations alone). The results so far show the importance of convective heat transfer to the unburnt fuel in the interior of the v-shaped junction to the rate of spread. Interestingly, this effect is not restricted to v-shaped junctions and can occur if a fire line is orientated at an angle non-normal to the driving wind, such as may occur during a change in wind direction. These findings will inform the development of simplified and idealised models that can be used operationally. Such models are crucial to predict fire spread in merging blazes and to account for changes in wind direction. The work on v-shaped fires is being extended to include v-shapes on slopes by an international collaboration involving researchers from Lebanon, France, Portugal, and Corsica, as well as Victoria University Melbourne, University of Melbourne, and UNSW Canberra.

Another area of interest has been the transport of embers from a bushfire. Embers are small burning pieces of vegetation that become airborne during a fire. These embers can travel considerable distances from a fire and are primarily responsible for the ignition of properties and new blazes (that can merge with the main fire front). Currently embers are largely considered as following ballistic trajectories, that is they become lofted by the plume and travel 100s of metres at least. My interest in this subject arises from the work conducted by Dr Rahul Wadhwani, who was a PhD student at Victoria University under the supervision on Prof. Moinuddin and I. The study consisted of developing an experimental setup to generate wind-borne particles and embers and a means of capturing the landing distribution of the embers. The experimental study was then used to test a range of drag models for different particles to predict of the ember travel distance and spread.

Recently, I have been working on simulation of gravity currents, intrusions of fluid which occur when a dense fluid is released into a lighter ambient fluid. An example of a gravity current flow is where sea-cooled air spills over a mountain range into the warmer inland air mass. This is a common phenomenon in summer on the south coast of New South Wales. In the summer of 2020, the current mixed with smoke from the black summer bushfires and transported smoke into Canberra. The smoke inundation of Canberra was directly responsible for one death and caused significant disruption to the city. In collaboration with Prof. Ooi (Mechanical Engineering) at the University of Melbourne as part of the Discovery project on gravity currents, we have conducted direct numerical simulations of lock-release planar gravity currents in a stratified ambient environment. Lock-release planar means the initial shape of dense fluid is a finite rectangular prism and the flow starts from rest. Stratification means the ambient fluid has a linear density profile which is lighter the top than the bottom; an unstratified ambient has uniform density everywhere. Our aim is to better understand the mixing processes that entrain ambient air into the head of the gravity current. Preliminary findings indicate that the while gravity currents propagate slower as the ambient stratification increases, the mixing efficiency of the gravity current increases considerably. The future direction of this work is to consider more complicated release shapes and continuous release currents, where dense fluid is continuously introduced to sustain the current.

My work is typically computationally intensive, each fire simulation requires approximately 6000 service units (SU) on Gadi at the National Computational Infrastructure. The numerical simulation of gravity currents is significantly more expensive requiring approximately 50,000 SU to complete one simulation. Currently I receive an allocation on Gadi under the partnership agreement between UNSW and NCI. These resources are also available through a merit allocation scheme. So far this year I have consumed approximately 2 million SU. The University of Melbourne maintains a smaller high-performance computer Spartan which is suitable for fire simulations.

In the next five years, after the completion of the two discovery projects, the direction of my research will be focused on constructing models of ember storms and ember attack from idealised coupled fire-atmosphere simulations. Embers are responsible for the majority of house losses in wildfires (60% of destroyed houses were found to be ignited alone in the Canberra 2003 fire)[5], however, the building standards (Australian Standard 3959 for Construction in bushfire prone areas[6]) prescribes measures largely to protect against radiant heat CITE AS3959. Very little is known about the transport embers that are transported by wind near or along the ground. LES provides a computationally tractable method of simulating flows over forested and urban regions, known as the wildland-urban interface (WUI). Models for creeping, saltating (bouncing), and the lofting of small particles exist in the literature, based upon the magnitude of the boundary shear stress. However, these models have not yet been applied to ember storms. By incorporating a model of creep, saltation, and lofting[7] into standard open-source CFD codes I will be able to simulate ember transport away from fire, represented as a region of high boundary temperature, through a forest, represented as an aerodynamic drag term, and over an idealised urban region, represented as an array of cubiod obstacles. These simulations will allow determination of threshold conditions for the onset of ember storms. The simulation results, which gives the path and the final landing distribution of the embers, will inform the development of an idealised model of ember accumulation. Areas of significant ember accumulation around structures is related to a high risk of ignition by embers. Established and relatively new machine learning methods, such as random forests and generative adversarial networks have been used to predict surface pressure fields in arrays of tall buildings and therefore may be a promising approach to predict surface shear stress and ember accumulation distributions in a WUI region. Alternatively, mass-conserving fluid models with building wake parametrisations, similar to those currently applied in pollutant dispersion modelling in urban environments, could be developed for embers. A model of ember storms that can be run in near real time would be a powerful design tool, allowing landscape architects to design suburban developments that minimise the accumulation of embers around individual houses. Developing sophisticated models of risk from ember storms is more challenging and would also involve developing models of ember genesis, ember combustion along its flight, and ignition propensity. More broadly, similar simulation and modelling techniques could be applied to the dispersion of seeds from invasive species, which has important ecological applications.

The emerging challenges, where high-fidelity physics-based modelling can provide insight, over the next decade in the broader field of wildfire spread modelling are developing idealised models of surge-stall propagation, fire attachment, fire whirls, vortex-driven lateral spread for operational purposes; and the development of faster than real time coupled-fire atmosphere simulations. Other emerging areas of interest are correctly incorporating stochasticity into partial differential equation spread models and the applications of data science and machine learning techniques to better predict the frequency, onset, and severity of wildfire events.

References

[1] Read, P. and Denniss, R., 2020. With costs approaching $100 billion, the fires are Australia's costliest natural disaster. The Conversation, 17.

[2] Sullivan, A.L., 2009. Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. International Journal of Wildland Fire, 18(4), pp.349-368.

[3] Miller, C., Hilton, J., Sullivan, A. and Prakash, M., 2015, March. SPARK–A bushfire spread prediction tool. In International Symposium on Environmental Software Systems (pp. 262-271). Springer, Cham.

[4] Moinuddin, K.A.M., Sutherland, D. and Mell, W., 2018. Simulation study of grass fire using a physics-based model: striving towards numerical rigour and the effect of grass height on the rate of spread. International journal of wildland fire, 27(12), pp.800-814.

[5] Leonard, J. and Blanchi, R., 2005. Investigation of bushfire attack mechanisms involved in house loss in the ACT Bushfire 2003.

[6] AS 3959. Construction of buildings in bush fire prone areas (AS 3959). Technical report, Standards Australia, Sydney, Australia, 2009

[7] Dupont, S., Bergametti, G., Marticorena, B. and Simoëns, S., 2013. Modeling saltation intermittency. Journal of Geophysical Research: Atmospheres, 118(13), pp.7109-7128.