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Linking Landscape Fires and Local Meteorology — A Short Review*

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Fires burning on 18th January 2003 generated a series of cumulonimbus clouds that probably exacerbated a fire that reached suburban Canberra. Powerful whirlwinds were generated, at least one of which might have been a genuine tornado. We briefly review the development of plume theory over the last fifty years and a potential atmospheric stability index that may assist in the identification of conditions that are conducive to extreme fire behaviour in the environment. This information can assist in deciding the location of future monitoring stations.

Key Words: Fires, Plumes, Atmosphere, Meteorology, Stability

1. Introduction

Fires in the landscape vary enormously in size. Small fires typically occur in light winds and only have minor associated plumes and induced winds. Large fires can induce very significant winds through the action of the large associated fire plume; even to the extent that "fire storms" can occur. These can then cause considerable damage and the fires can be very difficult to contain and extinguish.

There has been ongoing research interest in the fluid dynamics of fire plumes and the interaction with the ambient meteorology. The occurrence of this aspect of environmental fluid dynamics in association with complex topography and extensive vegetation makes this one of the more difficult areas for detailed simulation and encourages the application of simplified models. The intention is to gain a better understanding of the basic physical processes and the way in which they interact with the ultimate intention of being able to identify useful indicators for the onset of extreme behaviour.

This paper will review some of the relevant investigations, beginning with the seminal papers in the 1950's by Yih(1) and colleagues(2). The intention is to provide a brief overview of some of the many aspects of fire plumes which have been considered by researchers over a fifty year period, to indicate how the links with models of the atmosphere have emerged as being vitally important, and to demonstrate how the enhanced understanding might be applied to extreme fire events that occur from time to time in fire prone environments.

We also note that a recent special issue of the International Journal of Wildland Fire (Vol.14, No.1, 2005) contains several valuable contributions to many aspects of fire-atmosphere interactions which we will not have space to discuss here, albeit with a distinct Northern Hemisphere bias.

2. Plume Theory

During World War II several researchers were interested in the use of line sources of heat to remove fog from airfields and they subsequently established the basics of laminar plume theory; see particularly Refs. (1) and (2). There followed considerable interest in plumes in general and the possible applications to blow-up fires(3), entrainment into fire without cross winds(4), free burning crib fires(5), momentum balances for plume modelling(6), laboratory studies of fire whirls(7), radiation effects(8), links with meso-scale meteorology(9), the role of pressure in generating fire wind(10) and the effect of wind profiles on fire development(11). The possible connection between vortices and crown fires has also been a popular topic for investigation; e.g. Refs. (13), (14), (17), (20) and (21). The review by Beer(19) provides a good overview of the interaction of wind and fire and the paper by Raupach(18) is a useful summary of the non-dimensional scaling of a fire plume subjected to ambient winds. Some of the research has found its way into monographs, such as Refs. (12) and

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(25) and with the advent of modern computational power, it has become possible to conduct detail numerical simulations of fire plumes in a cross flow[26),(27)]. There have also been attempts to apply the modelling principles to ecological studies[(29)]. Despite these (and other) researchers having the best of intentions, none of this work has become a regularly used tool by ecologists or land managers, principally because the information needed to apply most of these modelling ideas is well beyond the scope of information that can easily, regularly and reliably be collected in the field. It is for this reason that there continues to be considerable interest in constructing simple, but hopefully effective, indicators of potentially extreme fire behaviour.

3. Haines Index

Investigations of the effect of atmospheric moisture on plume evolution[(15)] and the atmospheric stability on landscape fire behaviour[(16)] resulted in the development of an index to identify conditions which may result in extreme fire events. It was initially dubbed the LAWI and subsequently named the Haines Index. Several land management agencies around the world have started to incorporate the Haines Index into their fire planning, prevention and prediction systems. The essential idea behind the index is that the potential for vertical motion of air in the atmosphere can be quite significant in deciding whether or not a fire grows to become a serious problem for containment. Visually, this can also be related to the smoke column above a fire, with particularly large smoke columns growing taller in unstable air, developing very strong in-draughts and being similar in many respects to well-developed thunderstorms. All of this has a feedback effect of increasing the overall fire activity. Also associated with this is the increased potential for “fire whirls” and even “fire tornadoes” as there is a considerable amount of rotational movement caused by the action of the coriolis force on the fluid that is entrained by the plume.

Finally, burning material can be lofted well ahead of the actual fire perimeter and such “firebrand” activity can become a very serious problem with certain fuel types. The likelihood of this “spotting fire” behaviour is of particular interest because of the associated extra risk to fire suppression crews and assets.

The Haines Index is based on calculating the temperature difference between the two heights where the air pressure is 700 and 850 hPa and also the dew point at the height where the air pressure is 850 hPa. Each of these two calculations is scored from 1 to 3 and the two are added together. This clearly provides a number which ranges from 2 to 6; with 2 or 3 representing a very low potential, 4 a low potential, 5 a moderate potential and 6 a high potential for extreme fire behaviour[(22),(35)].

There is a suggestion that using the Haines Index in association with a locally derived fire danger index is a superior method for deciding upon the alert level for fire suppression activities. For example, in parts of Australia it may be best to combine the use of the McArthur index with the Haines Index whenever the latter achieves a value of six (or maybe even a five).

Irrespective of the current bias of land management agencies with regard to use of any particular fire danger indices or fire spread models, there is a real need to independently assess the reliability of the Haines Index both against extreme examples of fires observed in the field[(28)] and against the best available simulations, such as the meso-scale meteorological modelling of Clark and colleagues[(23),(24)]. Only in this way will it be possible to unambiguously determine which (if any) index or non-dimensional parameter is of generic use in predicting features such as the transition from a fire driven by wind to a fire where the fire plume itself is a significant factor in the local meteorology.

4. Canberra Fires, 18 January 2003

On the 18th January 2003, ten days after lightning ignition of fires in mountainous countryside, a significant fire storm reached suburban parts of western Canberra and resulted in the destruction of over 500 houses and the loss of four lives. The rugged terrain and the remoteness of these fires made them difficult to extinguish in the early stages, but the weather conditions were not too extreme and the fires spread relatively slowly, averaging about 2 km per day over the first 8 days. On 17th January the fire-spread was more rapid, but was still not showing particularly unusual features. The 18th January was very different. At one stage, the fires advanced through more than 10 km in 45 minutes, entering the west of Canberra. The heat generated by the fires as well as the water vapour released in the combustion products were sufficient to generate cumulonimbus clouds that rose to a maximum height of about 16 km[(31),(32)].

The ‘firestorm’ was partly distinguished by the appearance of powerful whirlwinds. One, in particular, left a trail of damage as it travelled about 16 km from a point in the mountains west of Canberra to finally enter some of the suburban areas. Figure 1 shows part of the pattern of damage caused to pine trees near the whirlwind’s inception. It could be that this was a genuine tornado, generated from the growing storm above and touching down where the damage was seen, although there is no truly conclusive evidence to prove this. A very substantial body of hot combustion products might have been able to generate a similar powerful rotation from below, in the same way that air above hot ground is able to generate whirlwinds, albeit greatly strengthened by heat from the combustion. The path of damage from the whirl is not continuous, having a gap of 2.1 km, which would be consistent with a tornado lifting off the ground and touching down again.

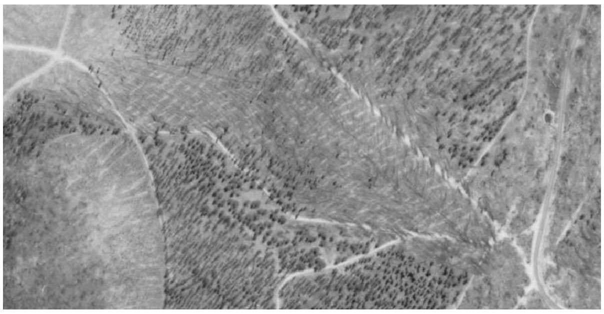

Fig. 1 The pattern of felled trees in this aerial photograph (21st January 2003 by AAM Photographics, Sydney) demonstrates the initial passage of a powerful whirlwind, or possibly a tornado, running diagonally across the picture

Broader details of the fire on and before 18th January have been outlined elsewhere. A commission of inquiry and the various submissions to it (all available online[30]) report some of the information. Other articles describe the atmospheric conditions on the day[31] as well as some aspects of the fire's development[32], [33]. Davis,[31], reports that the Haines Index for the 18th of January 2003 was 6 (as high as possible), but notes that this is not unusual for dry summer conditions typically experienced in inland Australia. Based on an estimated fuel consumption of 3 kg per square metre, McRae[32] points out that the fire released the energy equivalent of about 350 kilotons of TNT in the afternoon of 18th January. To the knowledge of the authors the kind of tornado or powerful whirlwind that accompanied the Canberra bushfire has not been documented or recorded in any other Australian bushfire to date. The fire spread very rapidly, possibly enhanced by semi-independent gaseous flame propagation. Although the relative humidity of the unburnt air was as low as 4%, the products of the fires contained considerable quantities of water vapour. This would have helped to generate the unstable atmosphere in which large quantities of moisture-laden hot air and combustion products rose into the stratosphere in a full-scale cumulonimbus cloud. It is conceivable that any such storm was intense enough to generate a tornado. Although direct evidence for this is not available, it is a circumstantial possibility and it needs to carefully examined from all possible angles, including the linked modelling of fires and meteorology described above. It should also be noted that recent research has indicated enhanced rates of fire-spread[34] well beyond those expected from existing formulae. This too may be partly due to the environmental flows induced by large fires. It may also be connected to the movement of pyrolysed gases, or at least an enhanced rate of heat transfer in vegetation. In any case, more detailed modelling of bushfires and the gas-solid, thermodynamic and chemical interactions in vegetation and the atmosphere above it are needed to help to gain a fuller understanding.

5. Conclusion

This paper has provided a selective review of some significant aspects of the interaction of wind and fire in the environment. As well as considering the modelling aspect, there is a brief synopsis of some of the events surrounding the Canberra fires of 2003. Subsequent to the fire storm reaching Canberra in 2003, a new automatic weather station at Mt.Ginini was added to the Australian Government's Bureau of Meteorology network. The intention of adding this station to the network is partially political and partially to provide earlier warning of the arrival of significant weather changes such as wind shifts and cold fronts, which have a strong bearing on potential fire danger and fire behaviour. This highlights the need for adequate monitoring in any region where meteorological factors impact on environmental conditions. It is imperative that all levels of community and government cooperate to ensure a best possible level of awareness of current situations and a timely awareness of the situation in the short term future. This way it will possible to at least provide adequate public warnings of impending extreme events.

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