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ABSTRACT

Fires that were attributed to lightning ignitions are examined for Victoria in south-east Australia. Lightning occurrence data are used to investigate atmospheric states at the time of the fire ignitions. Factors influencing the chance of fire per lightning stroke are examined, including seasonal and diurnal variations, as well as the influence of fuel moisture and weather parameters. The fuel moisture parameters of the Canadian Fire Weather Index System are found to be useful in indicating whether or not a fire will occur, given the occurrence of lightning. The occurrence of 'dry lightning', i.e. lightning which occurs without significant rainfall, is found to have a large influence on the chance of fire per lightning stroke. Through comparison of the results presented here for south-east Australia with the results of studies from other parts of the world, a considerable degree of universality is shown to exist in the characteristics of lightning-fires and the atmospheric states associated with them. For example, a method for forecasting dry lightning in the Pacific Northwest U.S.A. based on temperature lapse and dewpoint depression shows reasonably similar results when applied to south-east Australian conditions.

1. INTRODUCTION

Lightning is the cause of many wildfires throughout the world. Understanding the processes through which lightning causes fires is therefore of importance, as a greater knowledge of these processes could be expected to produce benefits such as reductions in the response time to these fires and thus a reduction in the damage that they cause. This report investigates atmospheric states that could potentially influence the chance that lightning will cause a fire, including the occurrence of 'dry lightning' - lightning that occurs without significant rainfall.

The probability of fuel ignition by lightning has been shown to be relatively independent of fuel moisture, with some fuels igniting even though they may be very wet (e.g. Latham et al. 1997). In contrast to the probability of ignition, the probability that an ignition is sustained is highly dependent on fuel moisture (e.g. Wotton and Martell 2005). The high dependency of ignition survival on fuel moisture is the reason why the concept of dry lightning is of importance. There are a number of ways in which dry lightning can occur: if a thunderstorm is high-based with relatively dry air at lower levels such that rain evaporates before reaching the ground (i.e. virga) or if a thunderstorm is fast moving such that the rainfall is spread thinly on the ground, or if lightning occurs outside of the rain shaft of a thunderstorm (commonly known as a 'bolt from the blue').

This study is the first systematic examination of the relationship between lightning occurrence and fires attributed to lightning ignitions (hereafter referred to as lightning-fires) ever undertaken in Australia. Nine years of lightning-attributed fire data are used together with lightning occurrence data to examine the atmospheric states associated with lightning-fires. A focus of this study is the application to south-east Australian conditions of a method for predicting dry lightning developed by Rorig and Ferguson (1999) in the Pacific Northwest of the U.S.A.. Their method uses a definition of dry lightning as lightning which occurs with rainfall of less than one tenth of an inch (i.e. 2.54 mm) and is based on high atmospheric instability (as represented by a large temperature difference between 850 hPa and 500 hPa) and low atmospheric moisture levels (as represented by high dewpoint depression at 850 hPa).

Intuitively, an ignition is less likely to survive if the fuel is already wet prior to the occurrence of lightning, regardless of whether the lightning is 'dry' or 'wet'. This means that the pre-existing state of the fuel moisture may be a factor in determining whether or not an ignition survives. The influence of the pre-existing fuel moisture is investigated in this report using the three fuel moisture components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987; Dowdy et al. 2009).

The following section describes the datasets used by this study, including lightning-attributed fire observations, lightning occurrence data, numerical weather prediction (NWP) forecasts of meteorological parameters, rainfall observations and fuel moisture conditions. This is followed by an examination of the characteristics of the lightning-attributed fire data and the lightning occurrence data, looking at features such as when lightning and lightning-fires are expected to occur. The influence of dry lightning on fire occurrence is examined in the next section, followed by an investigation of the relationship between lightning-fire occurrence and traditional fire weather parameters (such as screen-level wind speed, relative humidity and temperature, as well as fuel moisture content). In the cases where similar research has been undertaken in other studies, the results presented for south-east Australian conditions are compared with results from other parts of the world.

2. DATASET PREPARATION

In this study, data from a variety of sources are compared, including fire occurrence and characteristics data, lightning data, rainfall data, atmospheric profile data obtained from numerical weather prediction (NWP) models and modelled fuel moisture data.

Fires attributed to lightning ignitions (as determined by response personnel) are studied using information obtained from datasets maintained by the Victorian Department of Sustainability and the Environment (DSE). The data include information such as the location of the fire ignition, the time that the fire was first observed, the time that it was finally brought under control and classified as being 'safe' (which provides information about the duration of a fire) and the total area burnt by the fire. The dataset includes fires which were ignited on public land (i.e. land managed by the state government of Victoria), as well as a small number of fires that were ignited on private land and spread onto public land, although fires ignited on private land have not been used in this study as this would produce significant inconsistencies in the data between different locations. This subset of the DSE fire database, consisting of lightning-attributed fires which were ignited on public land, comprises our 'lightning-fire' dataset.

Lightning data were obtained from the commercial provider GPATS Australia. The GPATS data are based on the time of arrival of the lightning discharge at a network of three or more radio receivers (e.g. Cummins and Murphy 2009). This technique can detect the multiple return strokes that can be contained within a single lightning flash, as well as distinguish between cloud-to-cloud and cloud-to-ground lightning. This report uses a broad-scale approach for combining the lightning data with the fire data (i.e. only using a daily temporal resolution, as well as an effective spatial resolution of ~10 km) and so imperfections in the lightning detection efficiency (such as if they are not 100% efficient at distinguishing between cloud-to-ground and cloud-to-cloud lightning) are not expected to significantly influence the results presented in this report. The lightning dataset also includes information about the polarity and magnitude of the lightning current, but not about the existence of long-continuing currents.

To classify whether a particular lightning stroke is 'wet' or 'dry', rainfall data have been obtained from a gridded analysis of rainfall observations (for details see http://www.bom.gov.au/climate/austmaps/metadata-daily-rainfall.shtml). The rainfall data represent the total rainfall for the 24-hour period up to 0900 local time including daylight saving (LT) which is 11 hours ahead of UTC. The grid resolution of the data is 0.05 degrees in both latitude and longitude, which represents gridded areas of about 5 km by 5km throughout Victoria.

NWP forecasts from MESOLAPS (Puri et al. 1998) have been used to provide horizontal, vertical and temporal resolution of parameters describing atmospheric state. MESOLAPS forecasts are currently produced each day at analysis times of 0000 UTC, 0600 UTC, 1200 UTC and 1800 UTC. Forecasts are available at multiple terrain-following vertical sigma (i.e. pressure scaled by surface pressure) levels, with a resolution of 0.125 degrees in both latitude and longitude for three hourly intervals, out to 48 hours past the analysis time. A known issue with the MESOLAPS forecasts is that they tend to underestimate wind speeds as compared with observations. To reduce this bias, wind speed is calculated here as the average of the 10 m wind speed and the gust speed (calculated as the peak wind speed in the mixed layer). This wind speed has been shown to provide useful forecasts of fire weather based on MESOLAPS forecasts, following the analysis of meteograms such as those described by Mills (2005).

The FWI System is used to examine fuel moisture conditions. The FWI System was selected, in preference to other fire weather indices, such as the McArthur Forest Fire Danger Index (FFDI)

(McArthur 1967) widely used in Australia, since it includes multiple fuel moisture components: the Fine Fuel Moisture Code (FFMC) representing the moisture content of fine fuels and litter on the forest floor, the Duff Moisture Code (DMC) representing the moisture content of loosely compacted decomposing organic matter and the Drought Code (DC) representing the moisture content of deep compact organic matter of moderate depth. These three components indicate fuel moisture conditions for three different fuel sizes/depths which is a level of detail that is valuable for this study. The fuel moisture components of the FWI System have been calculated from noon NWP forecast values of temperature, wind speed and relative humidity (from MESOLAPS) and gridded analyses of rainfall observations (Weymouth et al. 1999). The FFMC, DMC and DC data consist of daily values, with a gridded resolution of 0.25 degrees in both latitude and longitude which represents a grid of about 25 km by 25 km throughout Victoria.

The various datasets used for this study, as described above, each have different periods of time for which data are available. The time period that has been used throughout this study is from 1 January 2000 until 31 January 2009; this is the maximum time period that is available for all of the datasets.

3. CHARACTERISTICS OF THE DATA

3.1 Lightning-attributed fire data

The temporal characteristics of the lightning-fire data (i.e. observations of lightning-attributed fires made by DSE Victoria) are shown in Fig. 1, based on the time that each fire was first observed. Distributions are shown for the number of lightning-fires that occurred during each hour, month and year (excluding 2009 since it only includes data for January). The lightning-fires are most commonly first observed in the afternoon (between about 1300-1900 LT). The fires are observed primarily from their smoke seen during daylight hours, which is likely to account for the jump in the number of fires observed after 0600 LT. About 96% of the lightning-fires occur between November and March, with January being the most common month for their occurrence. Considerable inter-annual variability is apparent in the number of lightning-fires which occur, ranging from about 60 in the year 2000 up to about 380 in the year 2007.

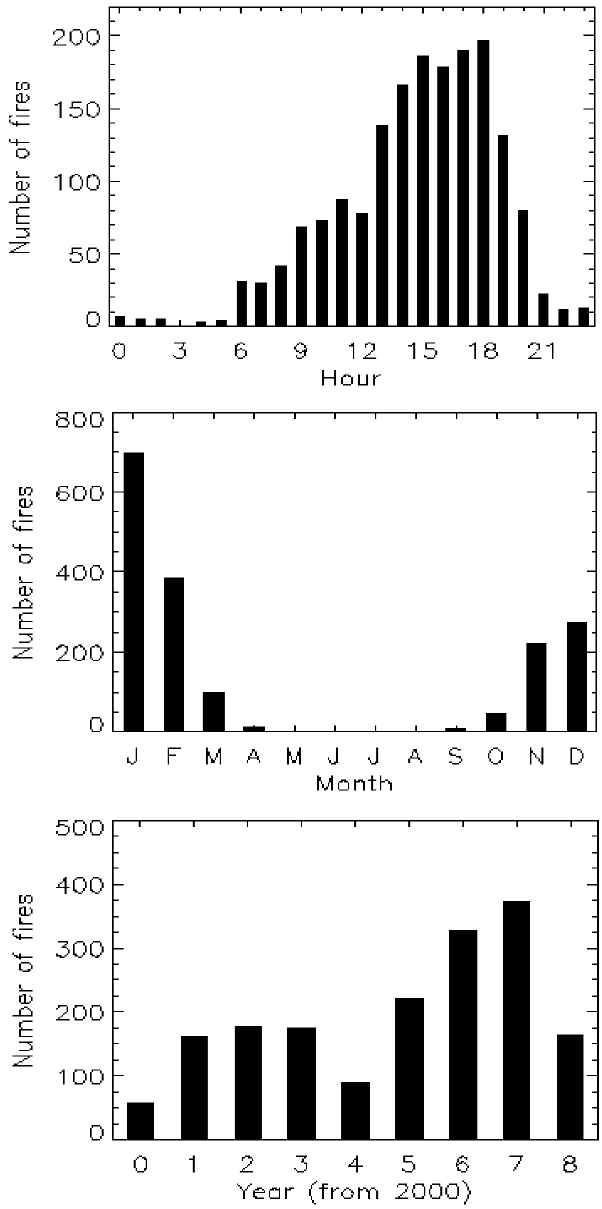

Fig. 1. The number of lightning-fires that occurred during the period of available data, distributed by hour (upper panel), month (middle panel) and year (lower panel), based on the time (in LT) that each fire was first observed.

Figure 2 shows the number of lightning-fires that occurred during the entire period of available data (from 1 January 2000 until 31 January 2009, distributed by the total area burnt by each fire and the duration of each fire. Lightning-fires that burn smaller areas generally occur more frequently than those that burn larger areas. The relationship between the size of the area burnt, A, and how often fires of that size occur, f, is reasonably linear when plotted using a logarithmic scale, indicating a power-law relationship:

$$f = 600A^{-0.45} \tag{1}$$

Lightning-fires account for about 90% of the total area burnt during the available period of data, even though they only account for about 30% of the total number of fires which occurred. This disproportionality can partly be attributed to the Victorian alpine fires of January-March 2003, which burnt about 1 million hectares, although even without this one large event lightning-fires still account for a high proportion (~55%) of the total area burnt by all fires.

This apparent disproportionality between the number of lightning-fires which occur and the large area that they burn has been observed in other parts of the world. For example, McRae (1992) reports that only about 5% of fires in the Australia Capital Territory are caused by lightning, but that they account for about 20% of the total area burnt, suggesting that this disproportionality is due to lightning-fires occurring preferentially in areas of the most rugged terrain which are difficult for fire crews to access. Wotten et al. (2005) report that about 48% of fires in Canada are caused by lightning, accounting for 85% of the area burnt, which they attribute to lightning-fires occurring in spatial and temporal clusters (due to large-scale connective storm systems) and also because lightning-fires occur frequently in remote areas where detection and suppression resources may be delayed in contrast to fires which occur in more built-up areas (e.g. Wotten and Martell 2005).

Figure 2 also shows that short duration lightning-fires generally occur more frequently than those of longer duration. The occurrence frequency of fires of a particular duration appears to roughly follow a power-law relationship, although there are considerable deviations from this relationship such as the relatively lower numbers of fires with durations of about 5-6 days or longer than about 20 days.

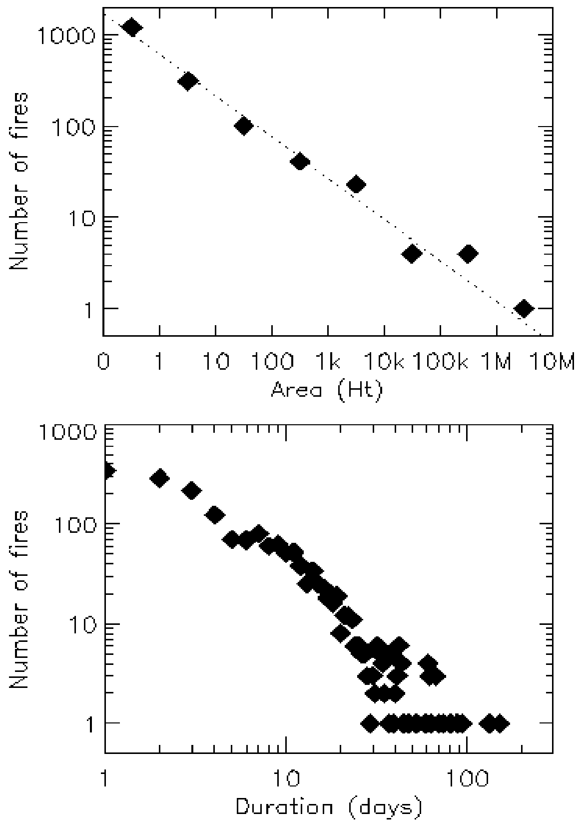

Fig. 2. Lightning-fire data, distributed by the total area burnt (upper panel) and the fire duration (lower panel), with a duration of 1 day indicating that the fire was classified as under control and safe within 24 hours of when it was first observed. The dotted line in the upper panel indicates the power-law relationship given by Equation 1.

3.2 Lightning data

The characteristics of the lightning occurrence data are examined in this section. The multiplicity of the lightning data (i.e. the number of individual strokes in a single lightning flash) is detailed in Fig. 3. The multiplicity has been determined by grouping strokes together for consideration as a single flash if they occurred within 0.5 seconds and 0.07 degrees (~7 km) in both latitude and longitude of the earliest stroke in a potential grouping (following the method of Richard and Lojou 1996).

Based on this methodology, the average number of strokes per lightning flash is about 1.5 for the data shown in Fig. 3. There is a good indication in Fig. 3 of a logarithmic decrease in the occurrence frequency of lightning flashes for increasing numbers of strokes per flash. The rare cases where the number of strokes per flash is very high could partly be an artefact of the method used, since the method distinguishes between different lightning flashes only when they are separated by more than 0.5 seconds and/or ~7 km. The results presented throughout this study are predominantly based on lightning stroke data as this provides better spatial accuracy than lightning flash data (produced by grouping strokes together as described above).

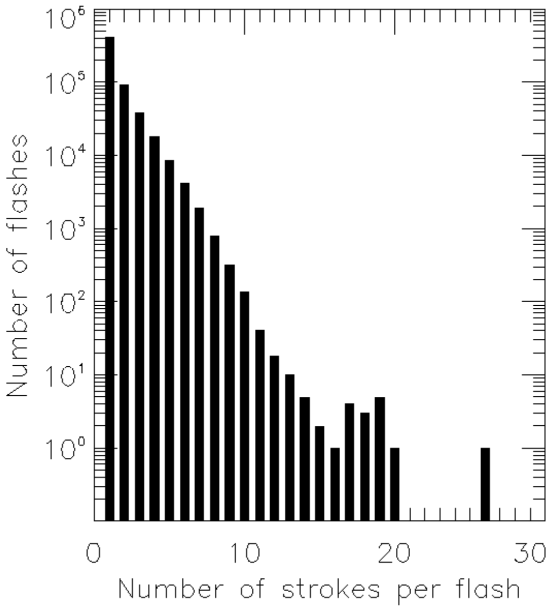

Fig. 3. Frequency distribution of lightning multiplicity.

Figure 4 shows the number of lightning strokes throughout Victoria in the available period of data, distributed by hour, month and year (excluding 2009 since it only includes data for January). The highest numbers of lightning strokes occur during the afternoon, as well as during the summer months. There is considerable inter-annual variability in the amount of lightning which occurs, with stroke counts varying by a factor of ~10 between the different years (excluding 2009 since it only includes data for January). There is some indication of an increasing trend in the amount of lightning which occurs, although this may be due in some part to increased sensor network density (due to new sensors being installed) as well as progressive upgrades being made to the sensors and data processing software.

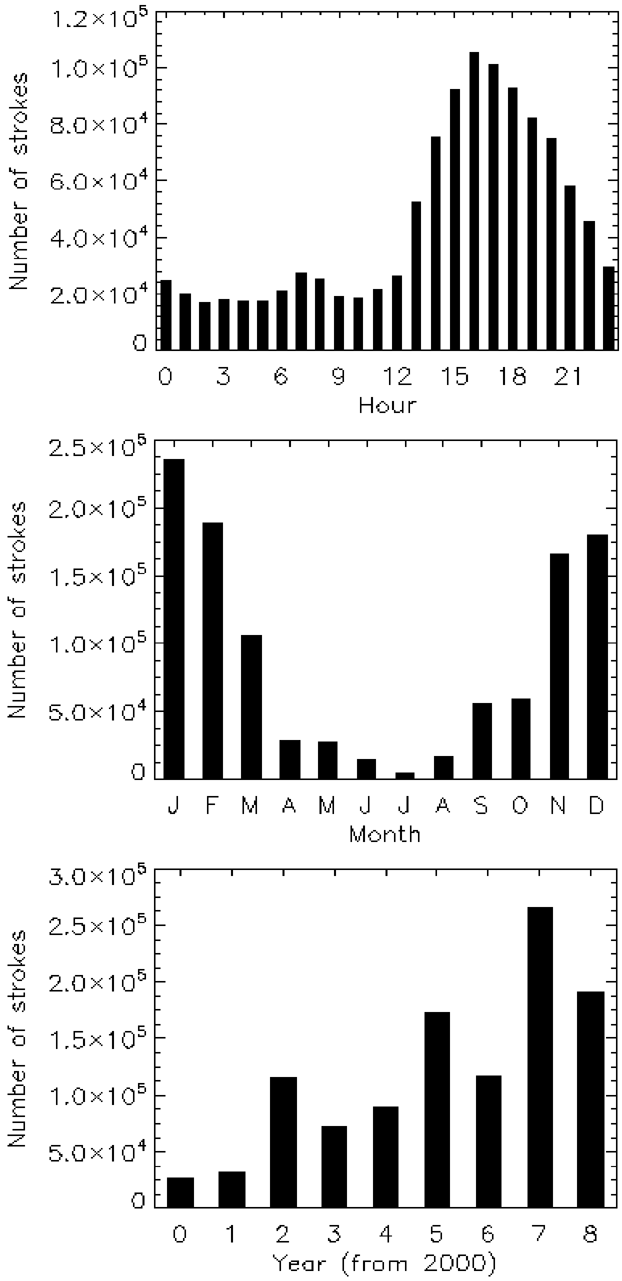

Fig. 4. The number of lightning strokes that occurred during the period of available data, distributed by hour in LT (upper panel), month (middle panel) and year (lower panel).

3.3 Combining the fire and lightning datasets

3.3.1 Determining ignition time

The way in which the ignition time of the lightning-fires was determined is detailed in this section. The ignition time allows the atmospheric conditions at the time of ignition to be examined in later sections of this study.

The lightning-fire data (as shown in Fig. 1) contains the time that a fire was first observed, not the time that a fire was ignited. The lightning-fire data can be combined with the lightning data to estimate the ignition time of each lightning-fire. The lightning stroke closest in time prior to the first observation of a lightning-fire is used here as the most likely fire ignition time, provided that the lightning stroke occurred within an area of 0.05 degrees (~5 km) in both latitude and longitude of the fire ignition location.

The time interval between our estimated ignition time and when a fire is observed for the first time is defined here as the smoulder period. The smoulder periods shown in Fig. 5 indicate that the vast majority of the fires grow large enough to be observed within a very short time interval after their ignition. It should also be noted that this time interval may be overestimated to some degree by the fact that fires are less likely to be observed at night or when fire spotting towers are not staffed.

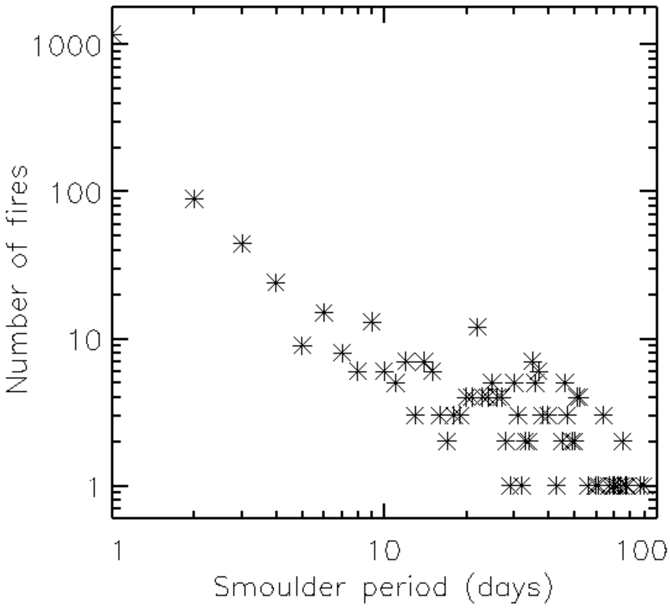

Fig. 5. A distribution of smoulder time, calculated as the number of days from the occurrence of lightning until when a lightning-fire is first observed.

In determining lightning-fire ignition times using the method described above, the chance that a particular fire is attributed to a particular lightning event purely by chance must be taken into account. The average time between days on which lightning occurs in Victoria is about 45 days based on a grid size of 0.1 degrees in latitude and longitude. If only the months November-March are considered, since this is when the majority of the lightning-fires occur, the average time between days on which lightning occurs is reduced to about 19 days. The fact that Fig. 5 shows that the vast majority of lightning-fires are observed within a very short time of the occurrence of lightning provides a high degree of confidence in the quality of the lightning and lightning-fire datasets, as well as in the method used to match the two datasets to each other.

A maximum smoulder time of 3 days is used throughout the later stages of this study, so as to provide a high degree of confidence in the lightning-fire ignition times. It is estimated that more than 99% of the smoulder periods are correct as shown in Fig. 5 for smoulder periods up to 3 days (see Appendix 1 for details), based on modelling lightning occurrence as a Poisson distribution with an average time between days on which lightning occurs of 19 days.

3.3.2 The average chance of fire per lightning stroke

The average chance of fire per lightning stroke is examined in this section, based on the number of lightning-fires in the dataset used for this study divided by the number of lightning strokes that occurred.

To provide spatial consistency with the lightning-fire dataset, lightning data are used here (and also for the remainder of this study) only at locations where a lightning-fire occurred at least once during the available period of data, with the lightning data and lightning-fire data gridded to the nearest grid point of the 0.05 degree resolution rainfall dataset. The grid points resulting from the above condition represent 12% of the area of Victoria, with a total of 131600 lightning strokes occurring at these locations during the available period of data. Given that about 39% of Victoria is publicly managed land, the total number of lightning strokes which occurred for all of the public land in Victoria during the available period of data can be estimated to be about 427700 (i.e. 131600*39/12). Scaling the number of lightning strokes using this method is expected to produce reasonably accurate results: for example, this method suggests that there should be about 1.1 million strokes (i.e. 131600*100/12) throughout the entire area of Victoria during the period of available data, which is the same as the actual value that occurs (based on the data shown in Fig. 4).

There are 1797 lightning-fires in the dataset used for this study. The average chance of fire per stroke is thus estimated to be ~0.4%, corresponding to 1797 fires resulting from 427700 lightning strokes. This represents an average chance of fire per flash of ~0.6%, given that there are about 1.5 strokes per lightning flash on average (Fig. 3). This is within the typical range of values reported for other parts of the world. For example, Wierzchowski et al. (2002) report that in Canada the average chance of fire from a single lightning flash is about 2% in British Colombia and about 0.07% in Alberta, citing factors such as elevation, spatial distribution of lightning, vegetation composition and fire weather conditions as the primary factors controlling lightning-fire occurrence. Larjavaara et al. (2005a) report that in Finland the average probability of fire from a single lightning stroke is 0.015%. This is considerably lower than the range of values typically reported in other countries possibly due to differences in fuel and climate types, or differences in fire reporting practices (e.g. Larjavaara et al. 2005b, suggest that between 63-70% of all lightning-fires are unreported in Finland).

3.3.3 The influence of lightning characteristics on the chance of fire

A number of different characteristics of the lightning data are examined here in terms of their influence on the chance of fire per lightning stroke, including the time that the lightning occurs, the polarity of the lightning and the flash multiplicity. To ensure the quality of the lightning-fire ignition data, a maximum smoulder period of 3 days has been used throughout the remainder of this study (accounting for 72% of the total number of lightning-fires in the dataset).

Figure 6 shows the seasonal and diurnal variability of the chance of fire per lightning stroke. The chance of fire per stroke has been calculated here (and for the remainder of this study) as the number of lightning-fires that occurred multiplied by 1.4 (to compensate for the fact that only 72% of the total number of lightning-fires were matched to lightning strokes with a smoulder period less than 3 days) divided by the number of lightning strokes multiplied by 39/12 (as discussed in the previous section).

A strong annual variation in the chance of fire per lightning stroke is apparent in Fig. 6, with the maximum chance of fire per stroke occurring during January (likely due to fuel moisture variations as investigated later in this study). In contrast to the annual variation, a large diurnal variation in the chance of fire per stroke is not apparent, although there is some indication of a relatively lower chance of fire from strokes that occur during the first few hours after midnight.

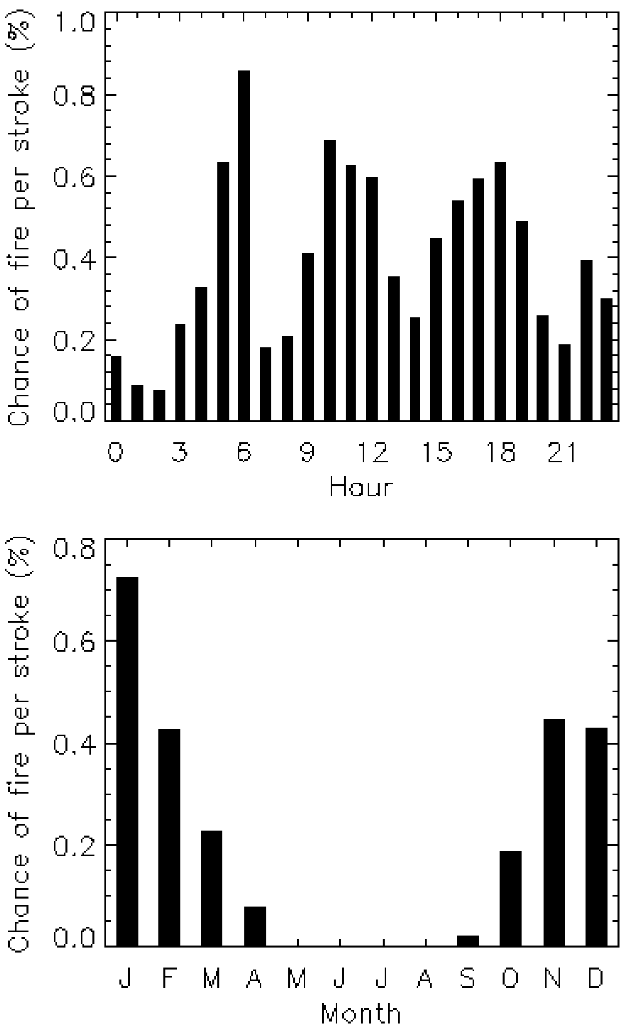

Fig. 6. The chance of fire per lightning stroke, categorised by the hour (upper panel) and month (lower panel) of the lightning (in LT).

The long-continuing current (longer than about 40 ms) that can sometimes be contained within a return stroke of a lightning flash is generally accepted to be the cause of most fuel ignitions by lightning (e.g. Fuquay et al. 1972). Uman (1987) reports that the probability of a long-continuing current is about 20% for a negative cloud-ground flash (which typically originate from the negatively charged lower parts of a cloud to the ground) and about 85% for a positive cloud-ground flash (which typically originate from the positively charged cloud tops to the ground). It could therefore be expected that positive lightning would be more likely to cause a fire than negative lightning. Larjavaara et al. (2005a) report for Finland that 11.1% of strokes are positive, causing 11.8% of fires. They conclude that polarity does not significantly influence the chance of ignition, which is in contrast to some results from North America (Kourtz and Todd 1991; Anderson 2002) who suggest that positive lightning is considerably more likely to ignite a fire than negative lightning.

For the data used in this study, it was not possible to determine whether or not positive lightning was more likely to cause a fire than negative lightning. Based on the lightning stroke closest in time prior to when the fire was first observed, provided that the stroke occurred within an area of 0.05 degrees (~5 km) in both latitude and longitude of the fire ignition location, the average chance of fire was 0.5% for positive strokes and 0.4% for negative strokes. However, this method does not unambiguously distinguish the actual individual lightning stroke that causes a fire, as a single thunderstorm may produce a large number of lightning strokes (and lightning flashes) within a small geographic area. When this method is repeated using tighter restrictions for the acceptable distance of a lightning stroke from the fire ignition position, it becomes less ambiguous as to which lightning stroke caused the fire, although this comes at the expense of reducing the number of fires that are successfully matched to lightning occurrence (due to the inherent limitations of the geographic precision of the datasets) such that significant results were unattainable. Similarly, the fact that the exact lightning stroke that caused the fire can not be unambiguously determined in many of the cases means that it was not possible to determine whether or not lightning flash multiplicity (i.e. the number of strokes per individual lightning flash as shown in Fig. 3) has a significant influence on the chance of fire per stroke.

4. DRY LIGHTNING

4.1 The relationship between dry lightning and fire occurrence

There are a number of factors which influence whether or not lightning causes a fire. The occurrence of dry lightning is one such factor, since an ignition is unlikely to survive if accompanied by heavy rainfall. To examine the relationship between dry lightning and the occurrence of lightning-fires, Fig. 7 shows lightning strokes distributed by the rainfall which accompanied them (using 1 mm bins to categorise the rainfall data). This is shown for strokes that were matched to fires as well as for strokes that were not matched to fires. The chance of fire per stroke is also shown for each rainfall amount.

The strokes that were matched to fires are most commonly accompanied by the lowest rainfall (i.e. from 0 mm to 1 mm), with a very rapid decrease in the number of fires which occur for increasing amounts of rainfall. In contrast, the distribution for all strokes exhibits a more gradual decrease with increasing rainfall. The difference between the two distributions is clearly illustrated by the chance of fire per stroke shown in the lower panel of Fig. 7, showing that dry lightning has a much greater chance of causing a fire than wet lightning. For example, if less than 1 mm of rainfall occurs the chance of fire per stroke is about 4 times higher than average.

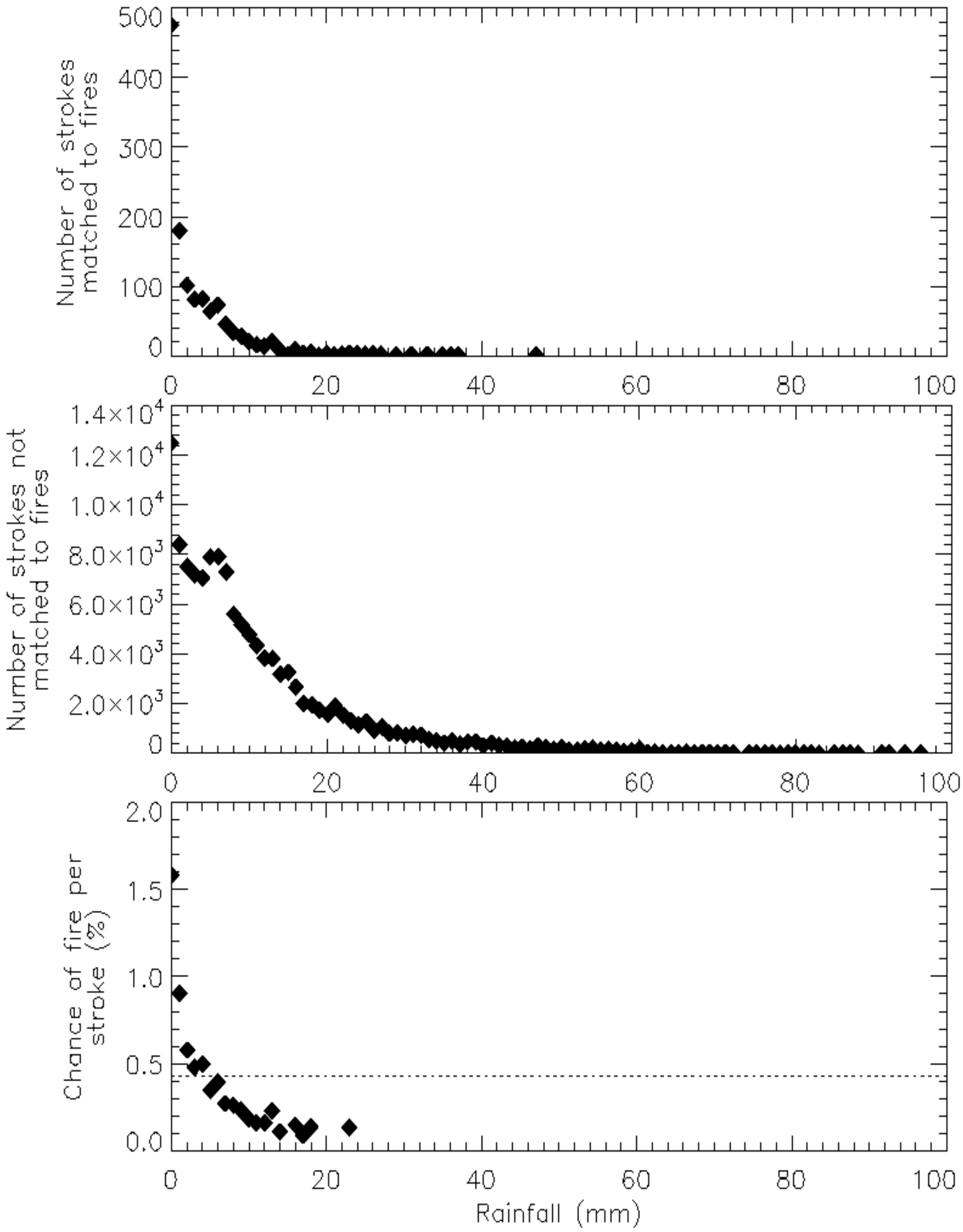

Fig. 7. The number of lightning strokes distributed by rainfall, shown for strokes that were matched to fires (upper panel) and for strokes that were not matched to fires (middle panel). The chance of fire per stroke is also shown (lower panel), with the dotted line representing the average chance of fire per stroke. The chance of fire per stroke has only been shown for values where the chance of fire per stroke multiplied by the total number of strokes is greater than 5 to avoid showing data that is based on very small sample proportions.

4.2 Atmospheric states associated with dry lightning

There have been relatively few studies determining the atmospheric conditions associated with the occurrence of dry lightning. Most notably, Rorig and Ferguson (1999) (hereafter RF99) showed that the occurrence of dry lightning in the Pacific Northwest of the U.S.A. was related to high instability (as represented by a large temperature difference between 850 hPa and 500 hPa) combined with low atmospheric moisture levels (as represented by high dewpoint depression at 850 hPa). RF99 found that the number of lightning-caused fires corresponded more closely to these two parameters than to the total number of lightning flashes that occurred. Their method correctly classified between about 56% and 80% of days on which thunderstorms occurred as either 'dry' or 'wet' as defined by a rainfall threshold of 0.1 inch (i.e. 2.54 mm).

This rainfall threshold for dry lightning in the Pacific Northwest of the U.S.A as used by RF99 is very similar to that for south-east Australian conditions, since the chance of fire per stroke (Fig. 7) increases very rapidly for rainfall amounts less than about 2-3 mm, with the average value occurring for rainfall amounts of about 4-7 mm. It should be noted that rainfall data used in this study are based on a gridded analysis of rainfall observations, whereas RF99 used station-based rainfall observations.

To examine the RF99 method for south-east Australian conditions, Fig. 8 shows lightning strokes categorised by the 850 hPa dewpoint depression (hereafter DPD) and the 850 hPa – 500 hPa temperature lapse (hereafter TL) for 1700 LT (obtained from the 0000 UTC MESOLAPS NWP analysis). Plots are shown separately for dry strokes and wet strokes, (using the 2.54 mm rainfall threshold to define 'dry' or 'wet' lightning), as well as the ratio of dry strokes to all strokes (i.e. the sum of the number of dry strokes and the number of wet strokes) to provide an indication of the chance of dry lightning. Lightning data are used only for the period 1500-1900 LT from the start of November until the end of March. This time restriction produces a more targeted analysis, since this is when the majority of the lightning-fire ignitions occur. RF99 used a similar targeted analysis period (from May-September, with DPD and TL data from 1700 local daylight time corresponding to 0000 UTC), although they did not determine ignition times of the fires and so fire data were used for all ignition times (whereas Fig. 8 uses fires thought to be ignited only during the period 1500-1900 LT).

The results shown in Fig. 8 are consistent with the results of RF99 for the Pacific Northwest U.S.A. in that a similar rainfall dependence and phase space is apparent. There is typically a high (low) chance of dry lightning for high (low) values of DPD and TL. This is also the case if fires are used for all ignition times throughout the day, which represents a more similar methodology to that of RF99. For extremely high values of DPD, there is some indication that TL plays a strong role in determining whether or not a fire will occur. For example, when *DPD* > 20˚C, there are almost no fires for *TL* < 34˚C, whereas almost all lightning strokes result in a fire for *TL* > 34˚C. It should be noted that the statistical significance of the results decreases as the values of DPD and TL tend towards their extreme values, e.g. due to the low number of lightning strokes that occur for *DPD* > 20˚C, although this is the nature of extreme events which occur very infrequently by definition.

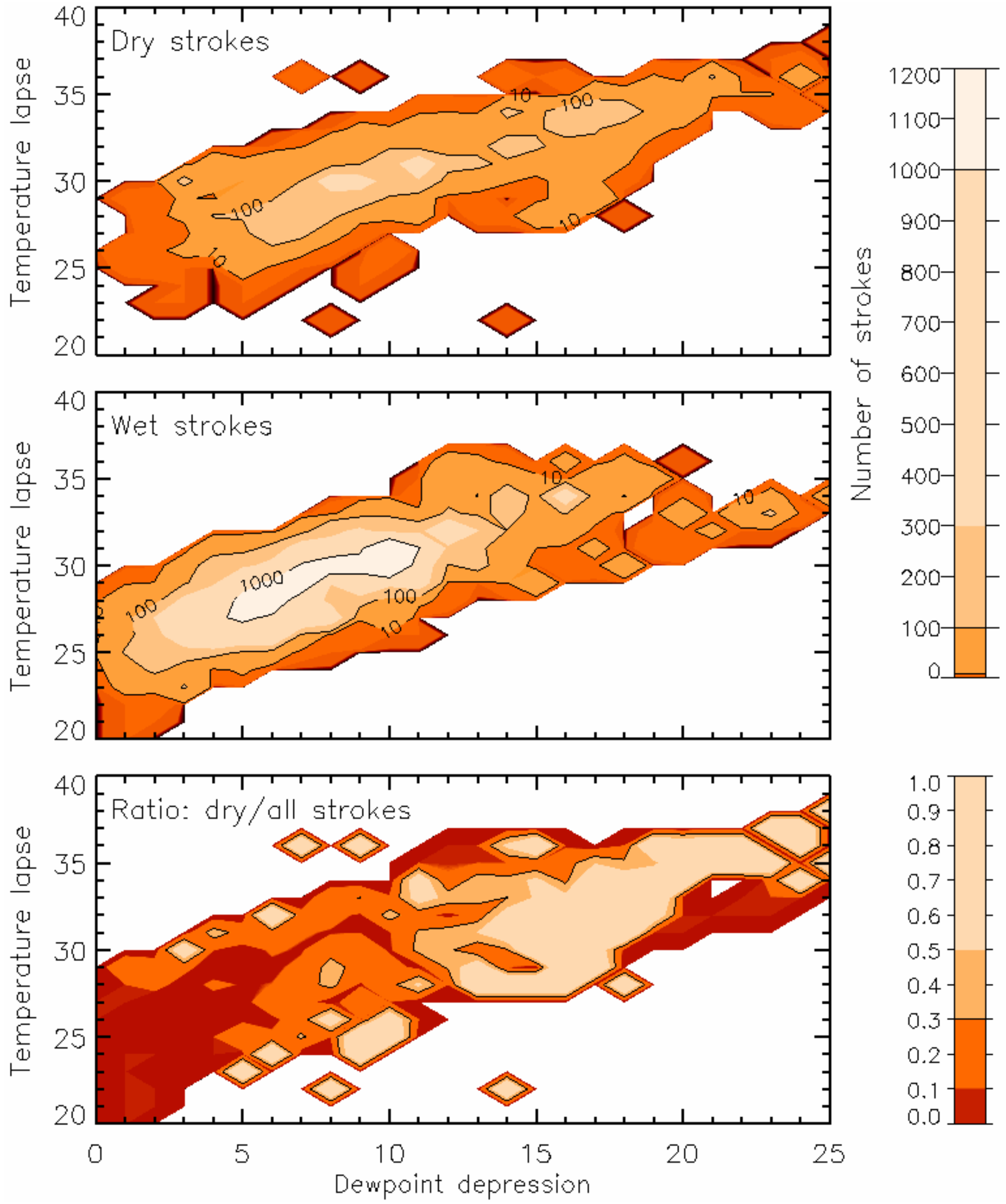

Fig. 8. The number of dry lightning strokes (upper panel) and wet lightning strokes (middle panel), distributed using the 850 hPa dewpoint depression and the 850-500 hPa temperature difference. The ratio of dry strokes to all strokes is also shown (lower panel).

Figure 9 shows lightning strokes categorised by the DPD and TL, shown separately for strokes that were matched to fire ignitions and for strokes that were not matched to fire ignitions. The ratio of strokes matched to fires to all strokes (i.e. the sum of the number of strokes matched to fires and the number of strokes not matched to fires) is also shown, providing an indication of the variation in the chance of fire per stroke. It is apparent that high (low) values of DPD and TL typically indicate a high (low) chance of fire per stroke.

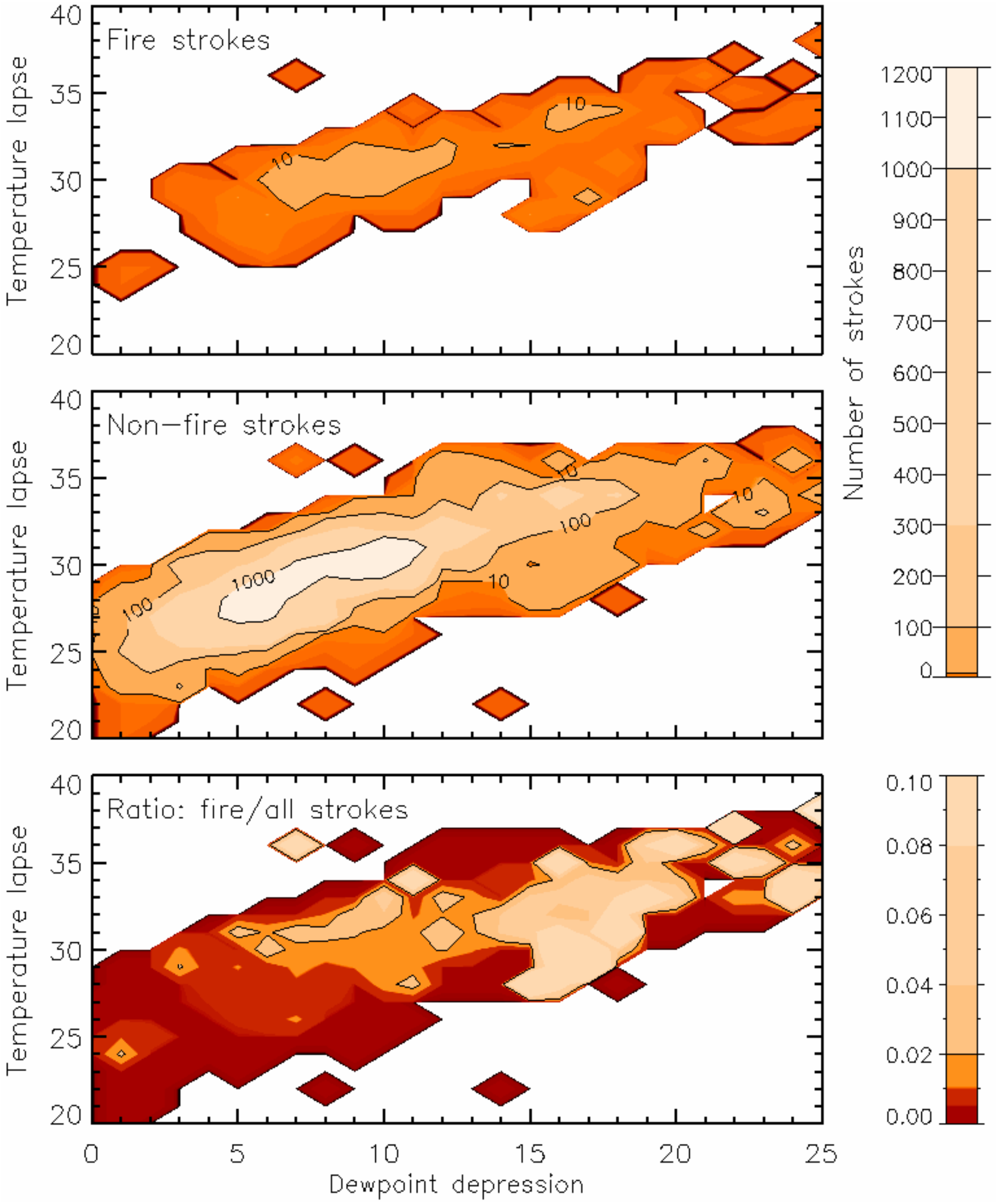

Fig. 9. The number of lightning strokes that were matched to a fire (upper panel) and the number of lightning strokes that were not matched to a fire (middle panel), distributed using the 850 hPa dewpoint depression and the 850-500 hPa temperature lapse. The ratio of the number of strokes matched to fires to the number of all strokes (lower panel) is shown to provide an indication of the variation in the chance of fire per stroke.

The dependence of the chance of fire per stroke on DPD and TL is very similar to what was seen for the occurrence of dry lightning (from Fig. 8). To examine if there is a direct causal link between the increased chance of dry lightning and the increased chance of lightning-fires, Table 1 shows the number of lightning strokes classified using thresholds values of 10˚C for DPD and 30˚C for TL, as well as 2.54 mm of rainfall for categorising the lightning as either 'dry' or 'wet'.

There are 12444 lightning strokes which occur for high DPD and TL from Table 1. It would be expected that from 12444 lightning strokes, about 2240 (~18%) would be classed as ‘dry’, since ~18% of lightning strokes are classified as ‘dry’ on average (i.e. ~18% corresponds to 334 +8140 dry strokes out of 46488 strokes in total). 2240 dry lightning strokes would be expected to produce only about 87 fires (since ~3.9% of dry lightning strokes are matched to fires: i.e. 334 out of a total of 334 + 8140 dry lightning strokes). The actual number of dry lightning strokes which occur for high DPD and TL is 3879 (i.e. 174 + 3705), which would be expected to produce about 151 fires (once again using the fact that ~3.9% dry lightning strokes are matched to fires). This means that the increase in dry lightning due to high DPD and TL accounts for an increase of 64 in the expected number of fires which occur (from 87 to 151). This leaves 23 (13%) of the 174 fires which occur for high DPD and TL unaccounted for, suggesting that high DPD and TL values may possibly be related to other factors (in addition to dry lightning) which also produce an increased chance of fire given the occurrence of lightning.

Table 1. The number of lightning strokes (as shown in Figures 8 and 9) categorised by thresholds of the 850 hPa dewpoint depression (DPD) and the 850-500 hPa temperature lapse (TL). These categories are shown cross referenced against whether or not the lightning stroke was matched to a fire and also by whether the lightning was classed as ‘dry’ or ‘wet’. Shaded values are referred to in the text.

		Fire		No fire		Total
		Dry lightning	Wet lightning	Dry lightning	Wet lightning	
DPD < 10˚C	TL < 30˚C	69	92	2936	21484	24581
	TL ≥ 30˚C	43	108	1044	6691	7886
DPD ≥ 10˚C	TL < 30˚C	48	14	455	1060	1577
	TL ≥ 30˚C	174	118	3705	8447	12444
Total		334	332	8140	37682	46488

5. IGNITION SURVIVAL

This section examines factors other than dry lightning that might influence ignition survival, including weather conditions (such as temperature, relative humidity and wind speed) and the role of the pre-existing state of the fuel moisture. Some discussion is also presented on the potential for forecasting the conditions that might lead to a greater probability of lightning-fire occurrence.

5.1 The influence of weather conditions

Lightning strokes are shown distributed by temperature, relative humidity and wind speed valid for 1700 LT (obtained from the 0600 UTC MESOLAPS analysis) in Figures 10, 11 and 12, respectively. They are shown for strokes that were matched to fires as well as for strokes that were not matched to fires. The chance of fire per stroke is also shown, together with the average chance of fire per stroke. The chance of fire per stroke has only been shown for values where the chance of fire per stroke multiplied by the total number of strokes is greater than 5 to avoid showing data based on very small sample proportions. The average chance of fire per stroke is higher than shown previously in Fig. 7 since only lightning strokes from 1500-1900 LT during the period from the start of November to the end of March are used here (to provide a more targeted analysis consistent with the data shown previously in Figures 8 and 9).

The temperature distribution (Fig. 10) has a maximum at 28-30˚C for strokes that were matched to fires, compared with 24-26˚C for strokes that were not matched to fires. In general, the higher (lower) the temperature, the higher (lower) the chance of fire per stroke, with temperatures above (below) 26-28˚C having a higher (lower) than normal chance of fire per lightning stroke.

Even though relative humidity is partly dependent on temperature, the distributions for relative humidity (Fig. 11) are considerably different to what was seen for temperature (Fig. 10). The relatively humidity distributions are less symmetric (skewed towards low values of relative humidity) than the temperature distributions, particularly for strokes matched to fires. In general, the lower the value of relative humidity the higher the chance of fire per stroke, with an average chance of fire per stroke occurring for relative humidities in the range of about 35-50%.

Wind speed (Fig. 12) does not appear to have a very large influence on the chance of fire per stroke within the range 10-30 km h^{-1}. This range of wind speeds accounts for the vast majority of lightning occurrence. Wind speeds above ~30 km h^{-1} correspond to an increased chance of fire. However, in contrast to temperature and relative humidity, there does not appear to be a range of wind speeds for which the chance of fire per stroke is greatly reduced. There is even some indication that very low wind speeds (less than 5 km h^{-1}) relate to an increased chance of fire per stroke.

Relative humidity appears to be a better indicator of the chance of lightning-fires than wind speed or temperature. For example, for the 100 fires with the lowest relative humidity (< 22%), the chance of fire per stroke is about 3.2 times the average value, whereas the chance of fire per stroke is only about 2.2 times the average value for the 100 fires with the highest temperatures (> 33˚C) and 2.5 times the average value for the 100 fires with the highest wind speeds (> 37 km h^{-1}). This order of importance relates to the chance that an ignition will be sustained, whereas for fire weather conditions in general (as represented by fire weather indices such as the FFDI and FWI) wind speed tends to have the largest influence on severe fire weather conditions in Australia followed secondly by relative humidity and then thirdly by temperature (Dowdy et al. 2009).

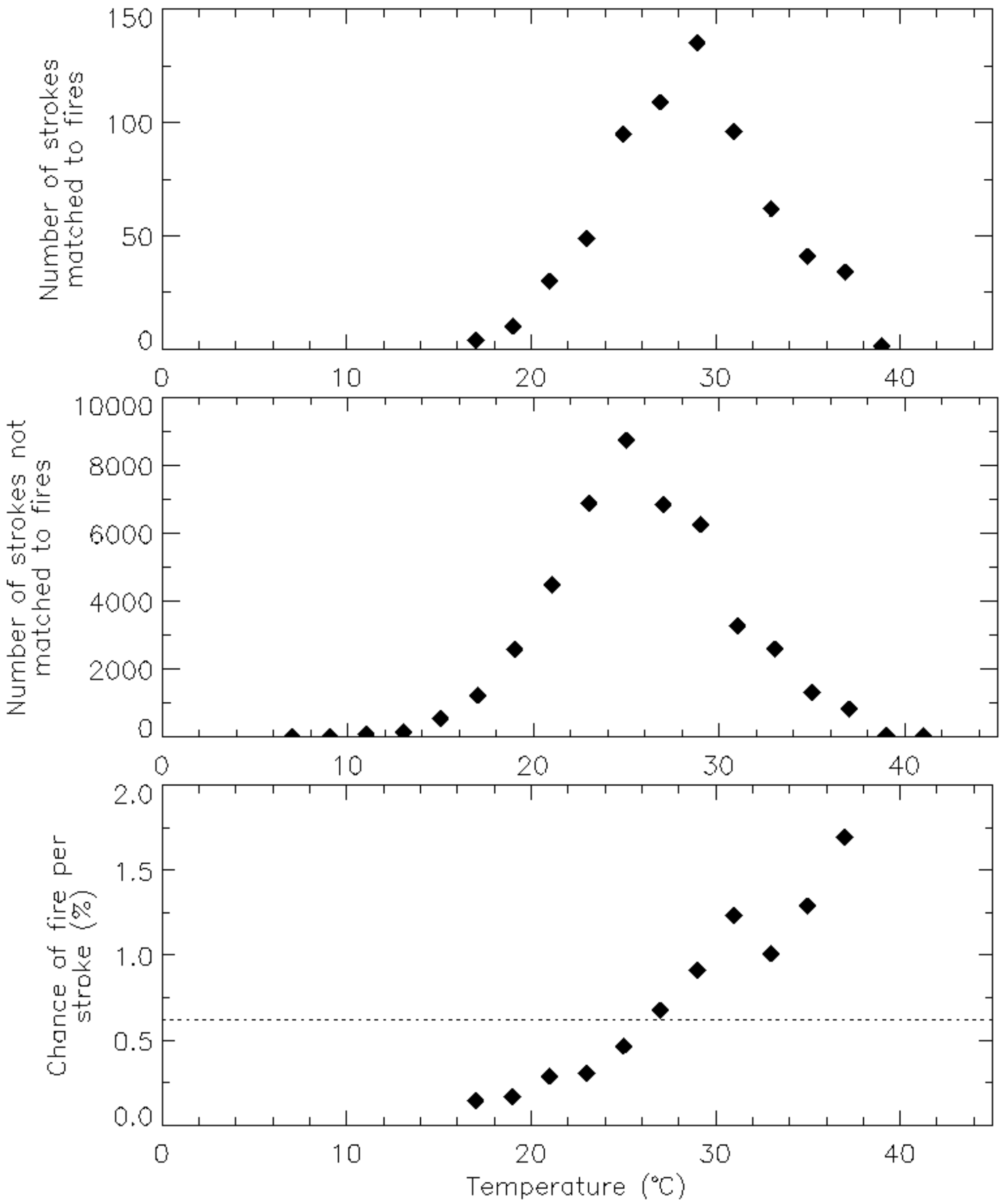

Fig. 10. As for Fig. 7, but for temperature.

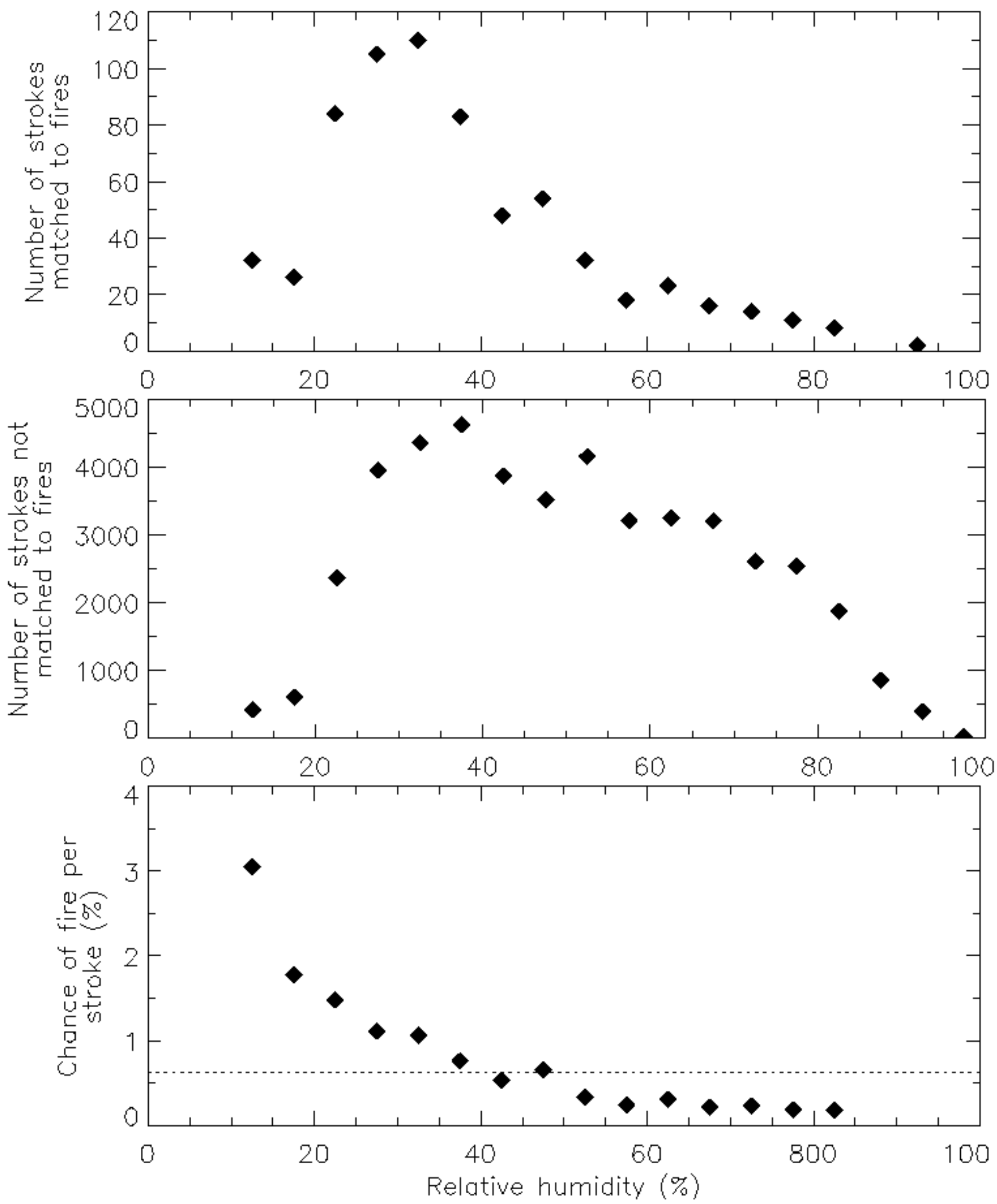

Fig. 11. As for Fig. 7, but for relative humidity.

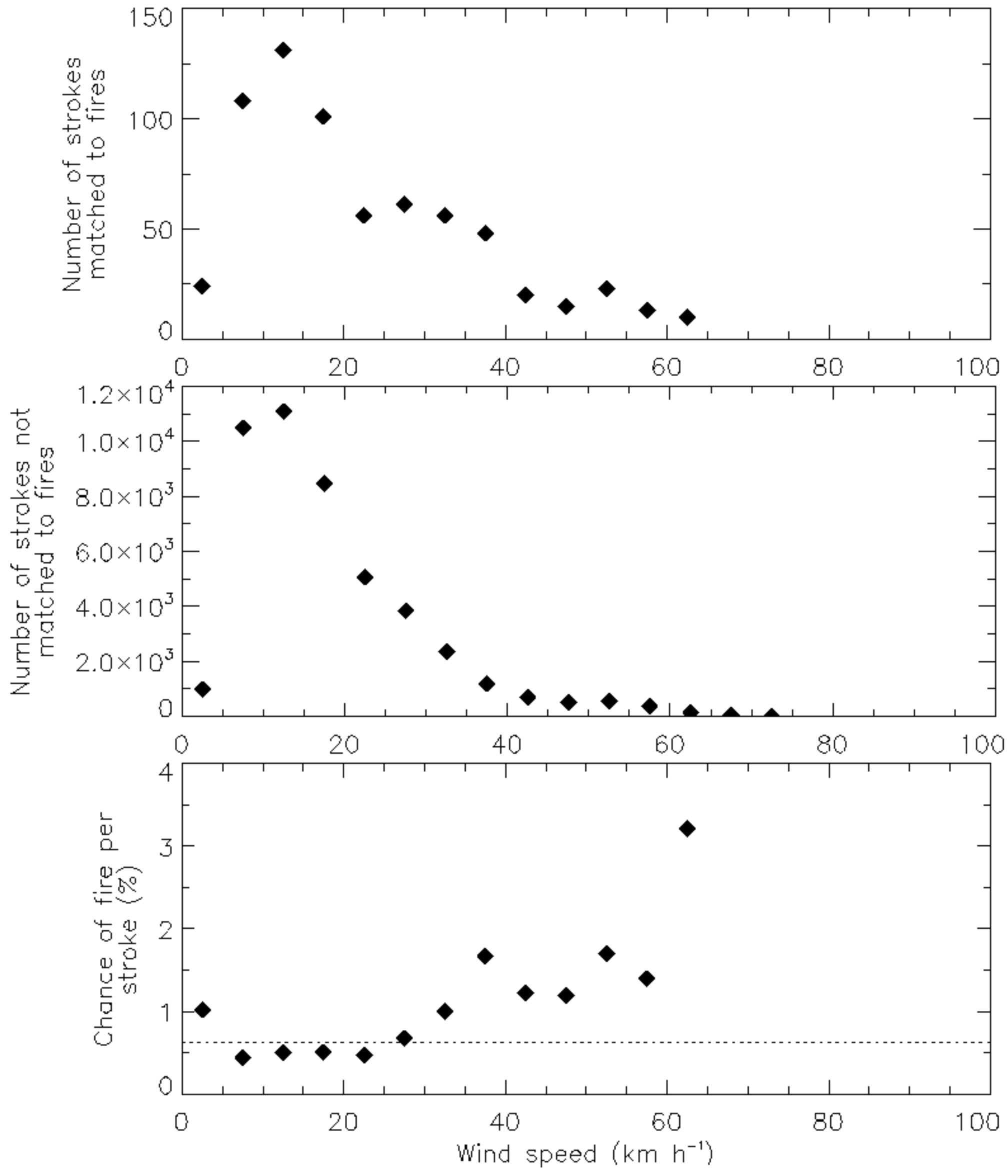

Fig. 12. As for Fig. 7, but for wind speed.

5.2 The influence of fuel moisture

Intuitively, an ignition is less likely to survive if the fuel is already wet prior to the occurrence of lightning, regardless of whether the lightning is ‘dry’ or ‘wet’. This means that the pre-existing state of the fuel moisture may be a factor in determining whether or not an ignition survives. The pre-existing fuel moisture, using the three fuel moisture components of the FWI System (the FFMC, DMC and DC), is in this section related to the lightning and lightning-fire datasets.

Figures 13, 14 and 15 show distributions of the FFMC, DMC and DC, respectively, for lightning strokes that caused fires as well as those that did not. As was the case in the previous section, lightning strokes have been used only if they occurred during mid-afternoon (from

1500 LT until 1900 LT) for the period from the start of November until the end of March. The values of the FFMC, DMC and DC represent the fuel moisture state prior to the lightning occurrence since they are based on 1200 LT conditions. The formulation of the FFMC is limited to values from 0 up to 101, while the DMC and DC can range from 0 upwards with no upper limit, with high (low) values of the fuel moisture components representing dry (wet) conditions.

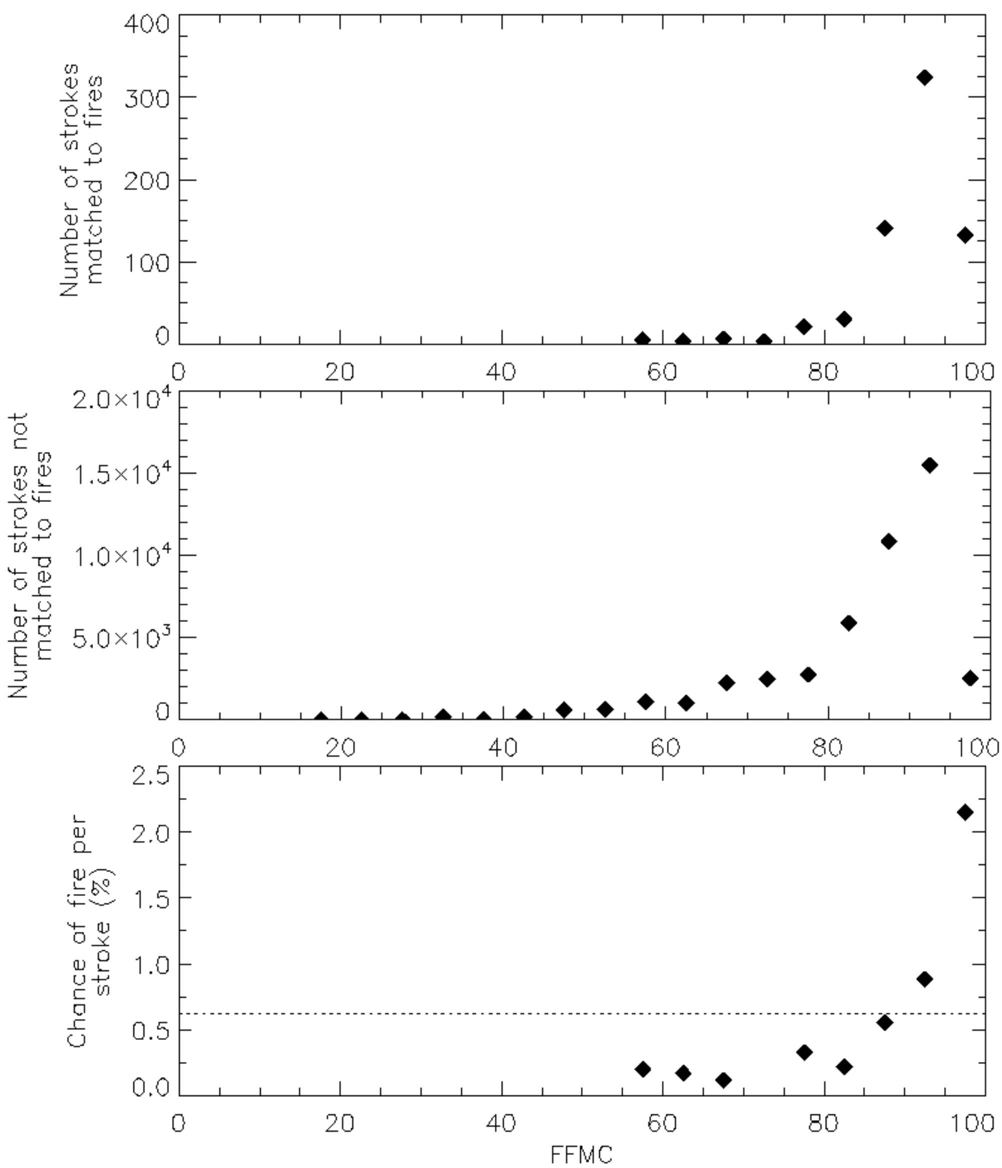

Fig. 13. As for Fig. 7, but for the Fine Fuel Moisture Code (FFMC) of the FWI System.

High values of the FFMC, indicative of dry fine fuels, correspond to a higher than average chance of fire per stroke (Fig. 13). This is also the case for high values of the DMC which indicate dry fuels of medium size or depth (Fig. 14), as well as high values of the DC which indicate dry fuels or large size or depth (Fig. 15). For the 100 fires with the highest FFMC values (> 95.4), the chance of fire per stroke is about 3.4 times the average value. In comparison, the chance of fire per stroke is only about 1.3 times the average value for the 100 fires with the highest DMC values (> 81) and 1.1 times the average value for the 100 fires with the highest DC values (> 713). This indicates that dry fine fuels (high FFMC values) are the best indicator of a high chance of fire from lightning, followed by dry fuels of moderate size or depth (high DMC values), with the dry fuels of large size or depth (high DC values) indicating only a slightly higher than average chance of fire per stroke.

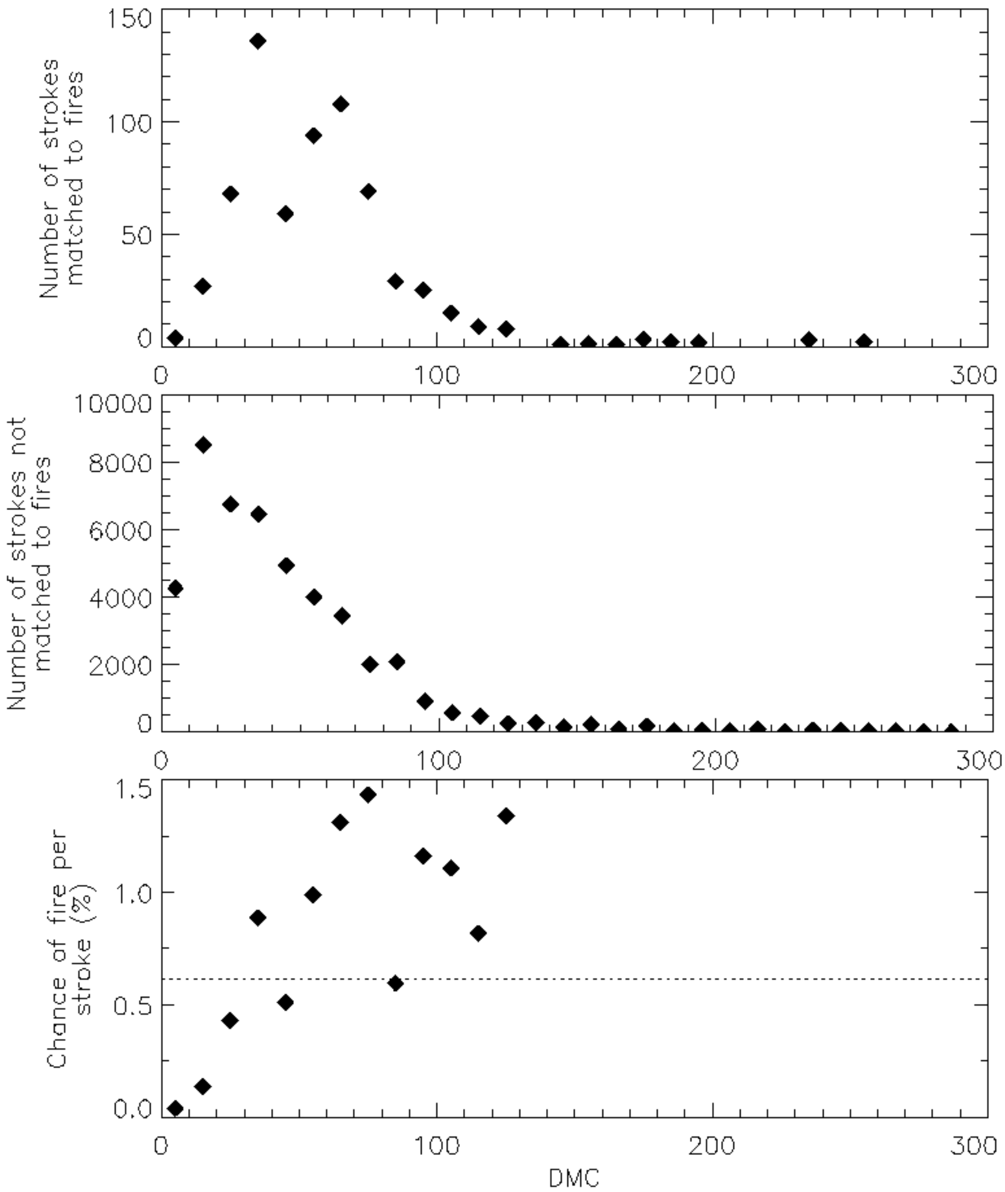

Fig. 14. As for Fig. 7, but for the Duff Moisture Code (DMC) of the FWI System.

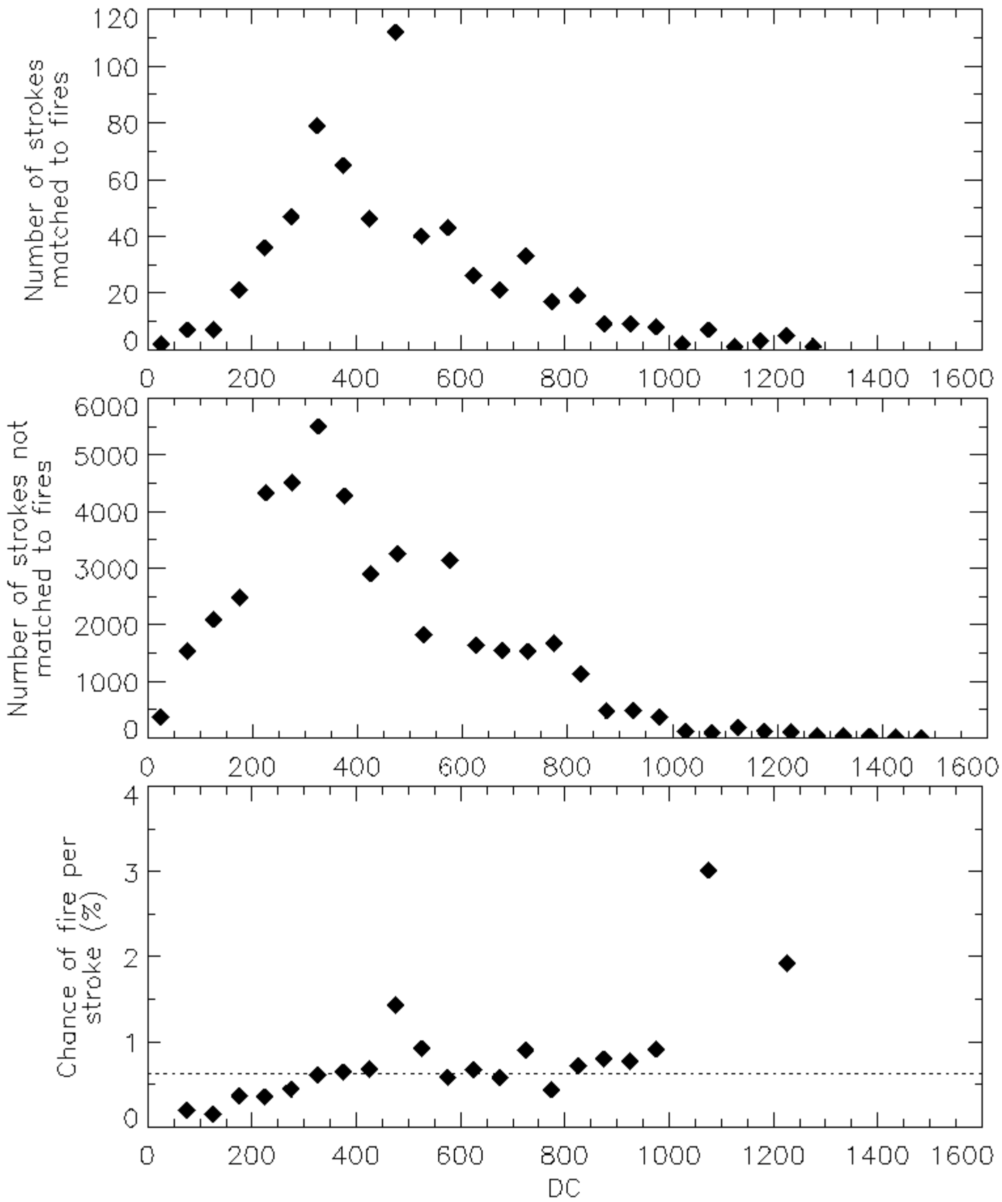

Fig. 15. As for Fig. 7, but for the Drought Code (DC) of the FWI System.

Low values of the fuel moisture components shown in Figures 13-15 tend to indicate relatively low probabilities that a fire will occur. However, there are numerous cases where a fire occurred even though a particular fuel moisture code was low, suggesting that the lightning ignition is being sustained by fuels of a different size or depth to the fuel type represented by that particular fuel moisture code. To examine this possibility, Table 2 shows the number of lightning-fires and lightning strokes categorised by low threshold values of the FFMC, DMC and DC. The threshold values of the fuel moisture components represent their 10th percentiles (i.e. high levels of fuel moisture) based on data for all lightning strokes (i.e. the sum of the number of lightning strokes that were matched to fires and the number of lightning strokes that were not matched to fires).

There is some indication in Table 2, based on conditional probability, that when one particular fuel type has high moisture content, an ignition can sometimes be sustained by one of the other fuel types. For example, when the fine fuel is wet (low FFMC), the chance of fire per stroke is 0.14% for *DMC* < 10.5 (i.e. 3 fires from 997 + 1085 lightning strokes) and 0.37% for *DMC* ≥ 10.5 (i.e. 9 fires from 261 + 2164 lightning strokes). When the DC is low, the chance of fire appears to be somewhat dependent on the FFMC as well as the DMC. However, when the DMC is low, fires are unlikely to occur regardless of the values of the other two fuel moisture components.

Of the three fuel moisture components, the chance of fire is lowest when the DMC is low, with only 4 fires having low DMC values. In contrast, there are 12 fires that have low FFMC values and 18 fires that have low DC values. This suggests that for high moisture content (i.e. low values of the fuel moisture components), it is the fuels of medium size or depth (as represented by the DMC) that are the most critical for determining whether or not an ignition will survive.

Table 2. The number of lightning strokes categorised by thresholds of the FFMC, DMC and DC. This is shown for lightning strokes that were matched to a fire occurrence as well as for all lightning strokes. The ratio of the number of fires to the number of lightning strokes is also shown for each category.

Fuel moisture levels			No. of fires	No. of strokes	Ratio
FFMC < 67	DMC < 10.5	DC < 165	2	997	0.20%
		DC ≥ 165	1	1085	0.09%
	DMC ≥ 10.5	DC < 165	0	261	0.00%
		DC ≥ 165	9	2164	0.42%
FFMC ≥ 67	DMC < 10.5	DC < 165	1	432	0.23%
		DC ≥ 165	0	2144	0.00%
	DMC ≥ 10.5	DC < 165	15	2960	0.51%
		DC ≥ 165	638	36445	1.75%

It is possible that some lightning-fire ignitions could smoulder for a number of days before a change in conditions occurs that extinguishes the smoulder without it ever growing large enough to be observed. To examine the conditions favourable for the survival of a smouldering fire, time series (not shown) of the fuel moisture components (FFMC, DMC and DC) and meteorological parameters (temperature, relative humidity and wind speed) were examined throughout the smoulder periods of the fires, although a repeatable pattern was not observed. The time series did not appear to provide any additional insight than was obtained from Figures 10-15 into the factors which determine whether or not a fire will result from the occurrence of lightning.

5.3 Forecasting the chance of ignition survival

It has been shown that there are a number of different factors which influence whether or not lightning will cause a fire, including DPD and TL, weather conditions (such as temperature, relative humidity and wind speed) and fuel moisture content. NWP-based forecasts are available for all of these factors suggesting considerable potential exists for forecasting the chance of fire given the occurrence of lightning. These forecasts would need to be combined with forecasts of thunderstorm potential (i.e. the chance of lightning) if estimations of the chance of lightning-fire occurrence were to be forecast.

Fire weather indices such as the FWI represent the combined influence of fuel moisture and weather parameters on aspects of fire behaviour. It might therefore be expected to some degree that the formulations of these indices would represent a reasonable methodology for combining the influence of the various different fuel moisture and weather parameters so as to forecast the chance of ignition survival. To examine this hypothesis, Fig. 16 shows distributions of the FWI for strokes that were matched to fires as well as for strokes that were not matched to fires. The chance of fire per stroke is also shown in relation to the FWI.

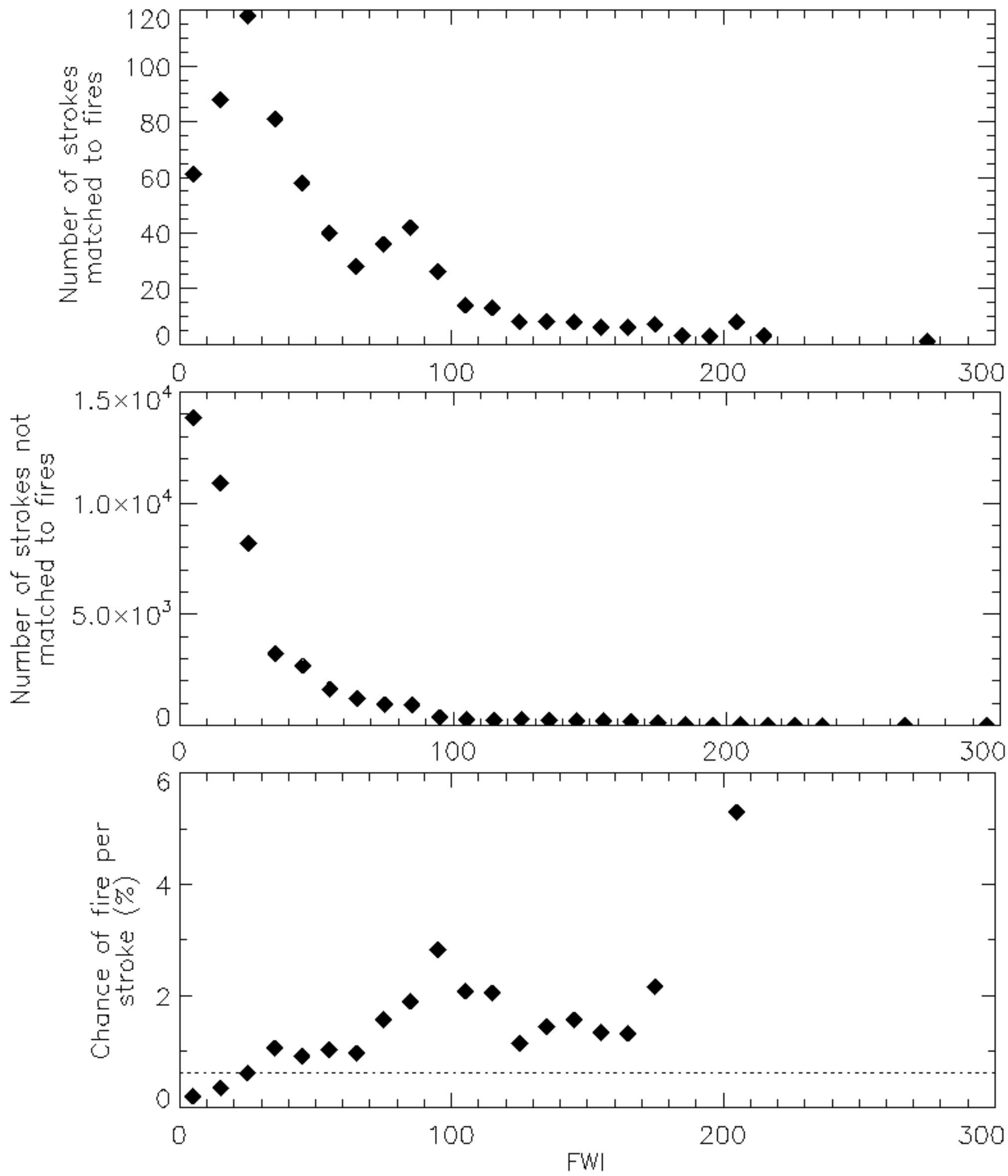

Fig. 16. As for Fig. 7, but for the FWI of the FWI System.

Very high values (e.g. ~200) of the FWI better indicate a higher chance of fire per lightning stroke than any of the individual fuel moisture or weather parameters examined previously (from Figures 10-15). However, these high FWI values occur so infrequently that they would not be particularly useful in applications such as daily operational forecasts of the chance of fire per lightning stroke. For example, for the 100 fires with the highest FWI values (> 94), the chance of fire per stroke is about 3.3 times the average value, which is about the same as occurs individually for relative humidity (3.2 times the average value) and the FFMC (3.4 times the average value). This suggests that the way in which the FWI formulation combines all of the various weather and fuel moisture parameters does not result in a large improvement over merely using relative humidity by itself (or the FFMC), indicating that combining the different factors which influence the chance of fire from the occurrence of lightning is not a straightforward matter.

A number of different methods of forecasting lightning-fires have been described in other studies. Wotton et al. (2005) showed that a modified version of the DMC was better than the DMC itself in predicting lightning-fire ignition in Ontario, Canada. They defined a Sheltered Duff Moisture Code which represents the amount of moisture in the upper part of the organic layer (the upper ~8 cm) in very sheltered locations near the boles of over-story trees. The Canadian province of Alberta and north-western Ontario use a threshold of *DMC* = 20 below which they assume lightning will generally result in unsustained ignitions, while in southern Ontario a threshold of *DMC* = 30 is used (Wotton et al. 2005). Based on the results shown in Fig. 14, it appears that a threshold of *DMC* = 20 might be more useful than *DMC* = 30 for south-east Australian conditions, since the chance of fire per stroke is reasonably similar to the average value for DMC values in the range 20-30.

It is intended that a forecasting method for the chance of fires caused by lightning will be developed for trial. This method is likely to be based on a combination of the DPD and TL (to include the influence of dry lightning) and the FFMC and DMC of the FWI System (to include the influence of fuel moisture and weather parameters), used together with forecasts of thunderstorm potential generated by the National Thunderstorm Forecast Guidance System (Deslandes et al. 2008).

6. DISCUSSION AND CONCLUSION

The characteristics of lightning-fires were examined for the state of Victoria in south-east Australia. This study represents the first ever systematic comparison of lightning occurrence data and lightning-fire data for Australia. Factors influencing lightning-fire occurrence were investigated, with a particular focus on dry lightning.

Lightning stroke data were matched to lightning-fire data to provide information about the time of fire ignition. It was found that the vast majority of the fires grow large enough to be observed within a short period of time from when they are ignited (~72% within 3 three days). This result is similar to results reported in other parts of the world, for example, Wotton and Martell (2005) for Canada report that at least 75% of fires are observed within the first 3 days after the occurrence of the lightning which was thought to have caused the ignition.

Lightning-fires were found to account for about 90% of the total area burnt, although only about 30% of all fires were attributed to lightning. This apparent disproportionality between the number of lightning-fires which occur and the large area that they burn has been observed in other parts of the world (McRae 1992; Wotten et al. 2005), reportedly due to factors such as lightning-fires occurring more frequently in remote areas and in spatial and temporal clusters than fires that are not ignited by lightning.

The average chance of fire per lightning stroke was found to be about 0.4%. This represents a chance of fire per lightning flash of about 0.6% (given that there was found to be about 1.5 strokes per lightning flash on average) which is reasonably similar in magnitude to values reported for other parts of the world (Wierzchowski et al. 2002).

It was found that the time of day that lightning occurs does not have a very large influence on the chance of fire per lightning stroke: most lightning-fires are ignited during the late afternoon, although this is also the time that most lightning occurs in Victoria. In contrast, a strong annual variation in the chance of fire per lightning stroke was observed, with the highest chance of fire per stroke occurring during January (~0.7%) even though this is when lightning most frequently occurs in Victoria.

A power law relationship was found to provide a reasonable estimation of the number of lightning-fires of a particular duration. This indicates that broadly speaking, fire duration has no 'typical value' in the sense that power law distributions are scale-invariant. Short duration fires tend to occur more frequently than long duration fires. The total area burnt by a fire also exhibited some indication of a power law relationship, with fires that burn smaller areas typically occurring more frequently than fires that burn larger areas.

It was found that if lightning occurs, the 'dryness' of the lightning has a large influence on whether or not a fire will result. For example, if less than 1 mm of rainfall accompanies the lightning then the chance of fire per stroke was found to be about 4 times higher than average. A method for predicting dry lightning developed by Rorig and Ferguson (1999) for the Pacific north-west U.S.A., based on the 850 hPa dewpoint depression (DPD) and the 850-500 hPa temperature lapse (TL), was examined for south-east Australian conditions. The rainfall threshold of 2.54 mm (i.e. one tenth of an inch) used by Rorig and Ferguson (1999) was found to have considerable relevance for south-east Australian conditions, with the chance of fire per lightning stroke increasing very rapidly for rainfall amounts less than about 2-3 mm (and the average chance of fire per lightning stroke occurring for rainfall amounts of about 4-7 mm). High (low) values of the DPD and TL were found to indicate a high (low) chance that lightning will be 'dry', with a phase space similar to that of Rorig and Ferguson (1999).

The climate of the Pacific Northwest U.S.A is considerably wetter and more humid than the south-east Australian climate, although it is similar in that lightning predominantly occurs in the mid-afternoon during the summer months. The fact that the relationship between dry lightning and the DPD and TL is reasonably similar in both regions indicates that the physics behind dry lightning may be somewhat universal: i.e. high-based thunderstorms with low atmospheric moisture at lower levels produce favourable conditions for the occurrence of dry lightning.

High (low) values of the DPD and TL were also found to indicate a high (low) chance that a fire will result given the occurrence of lightning. It was shown that the increased chance of dry lightning for high DPD and TL is likely to account for most (64 out of 87) of the estimated increase in the number of fires which occurred for high DPD and TL. However, this is still 23 fires short of the 174 lightning-fires which occurred for high DPD and TL, indicating that high values of these parameters may be related to other factors (in addition to low rainfall) which also produce an increased chance of fire given the occurrence of lightning.

The DPD and TL parameters are very similar to those used in the Haines Index (HI) (Haines 1988), which is a likely candidate for explaining the increase in fire occurrence that is not accounted for by the increased dry lightning occurrence for high DPD and TL. The HI is a fire weather index used frequently in the U.S.A to measure the potential for existing fires to become large fires. The formulation of the HI is based on the stability and moisture content of the lower atmosphere as represented by the dewpoint depression and temperature difference at a variety of different pressure levels (e.g. different pressure levels can be used for different elevations). The HI has been shown to be a valuable indicator of the potential rapid growth of fires in the western U.S.A., although Rorig and Ferguson (2002) suggest that the HI is of limited use for indicating dry lightning and lightning-fires as its categories are too coarse. The HI has also been proposed as a useful measure of potential fire activity in some regions of southern Australia, including Tasmania (Bally 1995) and south-west Western Australia (McCaw et al. 2007). Mills and McCaw (2009) show that statistically extreme values of their extended 'Continuous Haines Index' occurred in several cases of lightning ignited fire outbreaks that they document.

Fuel moisture and weather parameters were also found to have an influence on the chance of fire per lightning stroke. Temperatures above ~26˚C, relative humidities below ~38% and wind speeds above ~30 km h^{-1} all indicate a higher than normal chance of fire given the occurrence of lightning. Lower temperatures and higher relative humidities corresponded to a low chance of fire, although this was not found to be the case for lower values of wind speeds. Relative humidity was found to be better at indicating a high chance of fire per lightning stroke than temperature or wind speed. This is in contrast to fire weather indices such as the FFDI and FWI for which wind speed tends to have the largest influence in Australia (Dowdy et al. 2009). Dry fine fuels (high FFMC values) were found to be the best indicator of a high chance of fire from lightning, followed by dry fuels of moderate size or depth (high DMC values), with the dry fuels of large size or depth (high DC values) indicating only a slightly higher than average chance of fire per stroke. For high moisture content (i.e. low values of the FFMC, DMC and DC), the fuels of medium size or depth (as represented by the DMC) were found to have the most influence in determining whether or not an ignition will survive.

There was some indication of ignitions surviving in one particular fuel layer, even though another fuel layer may be too wet. This phenomenon has been reported previously in other studies (e.g. Muraro and Lawson 1970). However, the results presented here also suggest that if fuels of medium size or depth have high moisture content (as represented by low DMC values), the chance that a fire will occur is very small regardless of the moisture content of the other fuel layers.

The results presented here for the state of Victoria in south-east Australia have shown strong similarities to results presented from other locations throughout the world, including the average chance of fire per lightning stroke, the disproportionately large area burnt by lightning-fires, the time period between when a lightning-fire is ignited and when it grows into a large enough fire to be observed, the relationship between the amount of rainfall that accompanies lightning and the chance that it will result in a fire, the atmospheric conditions associated with the occurrence of dry lightning and some aspects of the influence of the pre-existing fuel moisture on the chance that a fire will result from the occurrence of lightning. Although some differences were also apparent, in general there is a considerable degree of universality between different parts of the world in the characteristics of lightning-fires and the atmospheric states associated with them.

The method of predicting dry lightning examined in this report (based on the DPD and TL) provides an indication of high-based thunderstorms with dry air at lower levels such that precipitation evaporates before reaching the ground. However, there are a number of other processes through which dry lightning can occur. These other processes provide scope for further research, including whether or not fast moving thunderstorms are more likely to cause fires than slow moving thunderstorms, as well as investigating the chance of fire from 'bolts from the blue' where lightning occurs outside of the rain-shaft of a thunderstorm.

It has been demonstrated that there are many factors which can be used to indicate the chance of fire from the occurrence of lightning. A number of these factors could be combined into an index which, when combined with lightning forecasts, could potentially produce forecasts of lightning-fire probabilities. Such an index could also be produced for statistical downscaling of lightning-fire occurrence from climate datasets (e.g. NWP climate simulations or reanalysis data). There have been relatively few studies into the influence of climate change on lightning-fire occurrence. A study by Price and Rind (1994) based on monthly averages of lightning-fire occurrence in the south-west U.S.A suggests a 44% increase in the number of lightning-caused fires for a doubling in atmospheric carbon dioxide level. Vazquez and Moreno (1998) report that the number of lightning-fires in peninsula Spain has been increasing. There is considerable scope for research into how lightning-fire occurrence could be expected to change in the future, particularly in southern Australia, as this is likely to be of importance both scientifically and in a broader social context.

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APPENDIX A: ACCURACY OF THE CALCULATED FIRE IGNITION DATES

For this study, the ignition time of a fire is taken to be the time of the lightning stroke that occurred closest in time prior to the first observation of the fire (given that the lightning occurred within 0.05 degrees in latitude and longitude of the fire ignition location). If there was no correlation at all between the lightning data and the lightning-fire data, ignition times calculated using this method would be based purely on the random chance of lightning occurring at the location of a fire at some time prior to when it was first observed.

To estimate the accuracy of the fire ignition dates (and the smoulder periods shown in Fig. 5), the probability, P, that lightning will occur at least once in a given area during a time period, τ, can be estimated based on Poisson statistics:

$$\mathrm{P}[\tau] = \sum_{k=1}^{\infty} \frac{e^{-\mu\tau}(\mu\tau)^k}{k!} \qquad \text{(A1)}$$

where μ is the average time between days on which lightning occurs in this area.

For μ = 19 days, as is the case for summer averaged for all 0.05 degree resolution grid points throughout Victoria, the probability that lightning will occur at least once during a 24-hour period is ~5.1% (from Equation A1). Of the 1797 lightning-fires which occur in the data set, it can be estimated that about 91 (i.e. 5.1%*1797) would have a smoulder period of 1-day if the lightning data were completely uncorrelated to the lightning-fire data.

This means that about 91 of the 1163 lightning-fires with a smoulder period of 1 day, as shown in Fig. 5, are likely to be due to the random chance that lightning occurred at the fire location within a 24 hours period prior to when the fire was first observed. Of the remaining 634 (i.e. 1797-1163) fires, about 32 (i.e. 5.1% of 634) would be expected to have a smoulder period of 2 days due to the random matching of the lightning and lightning-fire datasets.

To estimate the number of smoulder periods (and ignition dates) that are incorrect in Fig. 5, the randomly produced proportion of the smoulder periods (estimated as described above) can be redistributed based on the 'pure' distribution (i.e. the distribution with the estimated random element removed from it). This suggests that only about 9 of the smoulder periods are incorrect as shown in Fig. 5 for smoulder periods less than or equal to 3 days (corresponding to about 0.7% of the total number of fires with smoulder periods less than or equal to 3 days). For longer smoulder periods, the proportion of incorrect values increases rapidly, so a maximum smoulder period of 3 days is used in this report to ensure a high degree of data quality.

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