Modelling Fuel Moisture Under Climate Change

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Abstract:

Fuel moisture, along with wind speed and fuel structure, is an important determinant of fire danger and fire behaviour. Changes in climate can be expected to result in changes in fuel moisture and this in turn will impact fire management by modifying the length and severity of the fire season and also by changing opportunities for prescribed burning. This paper examines the effect of climate on fuel moisture in Australian Eucalypt forests.

We use the CSIRO CCAM climate model to predict weather conditions for five Australian cities (Brisbane, Sydney, Canberra, Melbourne, Hobart) from 1961 to 2100 using a high emissions scenario. Time series of weather conditions were extracted from the climate model predictions for each city and used as boundary conditions for a process-based fuel moisture model. The model represents fluxes of energy and water in a litter bed composed of litter, air, and free liquid water on the surfaces of the litter, bounded above by the atmosphere and below by the soil. The heat and water budget of each of the three materials is calculated at five equally spaced nodes within the litter layer using equations for litter temperature, the temperature of free liquid water on the litter surfaces, air temperature, litter moisture content, amount of liquid water on litter surfaces, and specific humidity. Physical processes that change these six quantities are represented in the model as fluxes of energy and water between the three materials at a given level, between levels within a given material, and between the litter layer and the atmosphere or soil. Fluxes of heat, water, and radiation between the litter layer and the soil or atmosphere are computed from boundary conditions: air temperature, wind speed, specific humidity, rainfall rate, solar radiation, thermal radiation, soil temperature, and soil moisture.

Fuel moisture predictions are used to examine two management variables: the number of days suitable for prescribed burning in spring, and the number of days when fire could burn in summer. To analyse the predictions, climate is characterised by two variables: average temperature and total rainfall. Average annual temperature increased at all sites by between 3.2 and 4.5°C century^{-1}. There was greater variation in rainfall but all sites recorded a negative trend in annual rainfall of between 83 and 141 mm century^{-1}. The range of temperature and rainfall in the later years of the model run (2009-2100) extended beyond the ranges simulated for current conditions (1961-2008). Seasonal mean temperature and rainfall were correlated at all sites. To simplify presentation of results, and because temperature and rainfall were correlated, principle components analysis was used to classify seasons as warm-dry or cool-wet. First principal component captured 71-80% of variance in spring and 61-76% of variance in summer.

There were significantly more fire days in warmer-drier years. The largest variation in fire days was seen at Brisbane, which also had the widest range of rainfall totals, with the wettest years having 0 summer fire days and the driest 82. The remaining sites had at least 18 fire days in even the coolest-wettest years and 80-90 fire days in warm-dry years. At all sites except Canberra there was an increase in the highest number of fire days from current to future climate.

Results for spring burning days were less clear. The range in burning days was narrower than for fire days (0-23 across all sites). Number of burning days decreased at all sites as warmer-drier years, but correlation with climate was weak, R^2 values were between 0.07 – 0.24. During spring the majority of days are either too wet or too dry, with a minority in the burning range. While the number of wet and dry days varies with climate, the number of transitional days did not vary systematically. Which climatic factors determine the number of burning days requires further detailed investigation of the fuel moisture curves for each location.

Keywords: *Bushfire, Climate change, Fuel moisture, Forest, Numerical Model*

1. INTRODUCTION

The moisture content of forest litter is an important quantity in fire management because it affects the ignition and propagation of bushfires. Above some threshold moisture content fuel will not burn and fires cannot ignite (Catchpole 2001). At the other extreme, very dry fuels ignite easily and this increases the likelihood of fires igniting or spot fires developing from already burning fires. Fuel moisture also plays an important part in prescribed burning because burns must be carried out when fuels are dry enough to sustain fire but not so dry that the fire is difficult to control. Fuel moisture is determined by short and long term weather patterns (Matthews 2006) and is thus susceptible to climate variability and change. This paper examines the effect of climate on fuel moisture in Australian forests and the implications for fire management.

The effect of climate change on fire has previously been examined by using the output of climate models to examine changes in fire danger metrics (Beer and Williams 1995, Brown et al. 2004, Cary 2002, Hennessy et al., 2005 Williams et al. 2001). These studies have used operational fire danger indices, e.g. the Forest Fire Danger Meter, (FFDM) that include empirical fuel moisture models (McArthur 1967). These models are limited in that they assume that the relationships between daily weather observations and changes in fuel moisture do not change, in particular, the FFDM assumes a constant drying rate after rain, irrespective of weather conditions. This study addresses this problem by using a process-based fuel moisture model which can respond to changing weather sequences. Previous studies have compared fire danger under current and future climate but have provided limited insight into the mechanisms of change and variability. Because there is uncertainty about the magnitude and for some variables, direction of future change, this study uses a different approach. Rather than compare present and future climate scenarios, we use a climate model with a high emissions scenario to generate a wide range of weather conditions and then relate fuel moisture metrics to climate metrics. These relationships can then be combined with climate change scenarios to predict changes in fuel moisture.

We use the CSIRO CCAM model to predict weather conditions for five Australian cities (Brisbane, Sydney, Canberra, Melbourne, Hobart) from 1961 to 2100. The climate model predictions are used to make fuel moisture predictions. The results are analysed in terms of two fuel moisture metrics: the number of days suitable for conducting prescribed burning in spring, and the number of days on which fire could burn in summer.

2. METHODS

The climate data set was created using the CSIRO Conformal Cubic Atmospheric Model(CCAM) (McGregor and Nguyen 2007). CCAM was first run from 1961 to 2100 for the entire globe at 200 km resolution using sea surface temperatures from the CSIRO Mk 3.5 climate model. The CCAM predictions were then downscaled to 20 km resolution over southeast Australia (Thatcher and McGregor 2008). Model runs were made under the SRES A2 scenario (SRES 2000). A2 is one of the higher emissions SRES scenarios, providing a large range of mean temperatures (Fig. 1.). Output from CCAM was stored in monthly files at 3-h (air temperature, rainfall, wind speed) and 6-h intervals (solar radiation, thermal radiation, specific humidity, soil temperature, soil moisture). Time series of surface variables were extracted from the nearest grid point to each selected location. The locations used in this study were: Brisbane, Sydney, Canberra, Melbourne, and Hobart. These cities were chosen to represent a range of climates in the fire prone south-east of Australia. All variables, except solar radiation, were transformed to 1-h intervals by linear interpolation. 1-h solar radiation was calculated by scaling a template curve by daily total solar radiation, to ensure the correct timing of dawn and dusk.

Fuel moisture predictions were made using the Matthews (2006) model. The model represents fluxes of energy and water in a litter bed composed of three materials: litter, air, and free liquid water on the surfaces of the litter. The litter bed is bounded above by the atmosphere and below by the soil. The model has one spatial dimension, height. The properties of the litter bed are assumed to be horizontally homogeneous and no horizontal transport is included. The heat and water budget of each of the three materials is calculated at five equally spaced nodes within the litter layer using equations for six quantities: T_m, litter temperature (K), T_l, the temperature of free liquid water on the litter surfaces (K), T_a, air temperature

(K), *m*, litter moisture content (kg water per kg of dry litter), *l*, amount of liquid water on litter surfaces (kg of water per m^3 of litter bed), *q*, specific humidity (kg of water vapour per kg of air). Physical processes that change these six quantities are represented in the model as fluxes of energy and water between the three materials at a given level, between levels within a given material, and between the litter layer and the atmosphere or soil. Fluxes of heat, water, and radiation between the litter layer and the soil or atmosphere were computed from boundary conditions: air temperature, wind speed, specific humidity, rainfall rate, solar radiation, thermal radiation, soil temperature, and soil moisture. To allow comparisons with field measurements of surface and profile fuel moisture the model predictions of litter moisture content and amount of surface water were combined:

$$S = m_1 + \frac{l_1}{\rho_{bulk}} \quad , \quad P = \sum_{i=1}^{N} \left(m_i + \frac{l_i}{\rho_{bulk}} \right) \quad , \quad A = 1 - \left(\frac{1}{1 + a\, e^{bP}} + c \right)$$

Where *S* is the total moisture content (kg kg^{-1}) of the top model layer, *P* is the moisture content (kg kg^{-1}) of the entire litter layer, A is the fraction of the fuel bed that is dry enough to burn ('Available fuel factor") (Beck 1995), m_i and l_i are the water content of the litter (kg kg^{-1}) and the free water content (kg m^{-3}) of the i^{th} model layer, ρ_{bulk} is the litter layer bulk density (kg m^{-3}), $N = 5$, $a = 0.43\, e^{23S} + 2$, $b = -85S + 2.4$, and $c = 1.3S - 0.43$.

At each site the fuel moisture model was parameterised to represent *Eucalyptus* forest on flat ground with a 30 mm deep litter layer, equivalent to 1.5 kg m^{-2} fuel load. This relatively heavy fuel load was selected to allow the model to respond to variation in drying conditions after rain. A very thin layer will always dry rapidly, and hence effects of variation in climate would not be seen. The model was driven using CCAM output as boundary conditions. The CCAM variables were transformed from standard meteorological measurements to within-forest values using the methods described in Matthews et al. (2007). The Matthews model was initialised in an arbitrary state and run from January 01, 1961 to December 31, 2099. The model equations were solved on a 1-h time step. The first 2 months of the run were not used in data analysis, to avoid dependence on the initial conditions. The Matthews model, originally implemented in Visual Basic for Applications within a spreadsheet, was rewritten as a Python script. The model run for each city took ~5 processor days.

3. RESULTS

We present results for two important management variables: the number of days suitable for conducting prescribed burning in spring, and the number of days on which fire could burn in summer. A prescribed burning days is defined as having available fuel factor between 0.3 and 0.7 (Sneeuwjagt and Peet 1998). A fire day is defined by surface fuel moisture <15% and profile moisture <25%. Fuel moisture can be combined with wind speed to calculate fire danger or with wind speed and fuel characteristics to predict fire behaviour. This analysis is beyond the scope of this paper.

Although climate models predict many meteorological quantities, most future scenarios have included temperature and rainfall as the most important and often only variables. More recent projects have also included solar radiation, wind speed, and specific humidity, although the prediction ranges have been larger than the mean predicted changes (CSIRO 2007). For this initial study we considered only two climate variables: mean temperature, and rainfall amount.

Average annual temperature increased at all sites by between 3.2 and 4.5°C $century^{-1}$ (Figure 1). There was greater variation in rainfall but all sites recorded a negative trend in annual rainfall of between 83 and 141 mm $century^{-1}$. Seasonal mean temperature, T, and rainfall, R, were correlated at all sites (Figure 2). The range of T and R in the later years of the model run (2009-2100) extended beyond the ranges simulated for current conditions (1961-2008) (Figure 1). To simplify presentation of results, and because T and R were correlated, principle components analysis was used to reduce the number of variables. The first principal component, PC1, axis for each season and site is shown in Figure 2. PC1 captured 71-80% of variance in spring and 61-76% of variance in summer. As seen in Figure 1, seasons with negative PC1 are relatively warmer and drier than seasons with positive PC1, so PC1 may be interpreted as an index of warm-dryness vs cool-moistness.

PC1 was significantly correlated with the number of summer fire days at all sites (R^2 between 0.66 and 0.78), with more fire days in warmer-drier years. The largest variation was seen at Brisbane, which also had the widest range of rainfall totals, with the wettest years having 0 summer fire days and the driest 82. The remaining sites had at least 18 fire days in even the coolest-wettest years and 80-90 fire days in warmer-drier years. At all sites except Canberra (where some years have 90 fire days) there was an increase in the highest number of fire days from current to future climate. As well as variation in the number of fire days, PC1 was correlated with the fuel moisture on any given day (Figure 3). In warmer-drier years the frequency of moisture contents below 10% is higher than in cooler-wetter years, implying a higher number of days with at least a given level of fire danger, given equal wind speeds.

Results for spring burning days were less clear. The range in burning days was narrower than for fire days (0-23 across all sites). Number of burning days decreased at all sites as warmer-drier years, but correlation with PC1 was weak, R^2 were between 0.14 – 0.48. Available fuel factor histograms show a majority of days are either wet, A=0 or dry, A=1, with a minority in the burning range, 0.3 to 0.7. While the number of wet and dry days varies with PC1, the slope of the cumulative frequency curves in the burning range varies only slightly. Because burning days occur in the drying phase after rain, this result indicates that during a wetter/drier spring there are longer/shorter wet periods but that number of drying cycles does not vary systematically with seasonal rainfall. What climatic factors determine the number of burning days requires further detailed investigation of the fuel moisture curves for each location.

4. DISCUSSION/CONCLUSIONS

Fuel moisture at five Australian sites was modelled by using a climate model and a process based fuel moisture model. The climate model simulations provided a set of physically consistent weather conditions that extend beyond the ranges of temperature and rainfall under current climate. Climate model output was used to drive the process-based fuel moisture model, generating 140 years of fuel moisture predictions. This large set of prediction enabled us to investigate sensitivity of fuel moisture to climate, something which has not previously been possible as observational data sets for Australia have been less than 6 months long (Matthews et al. 2007). Full analysis of the climate and fuel moisture data sets produced for this was beyond the scope of this paper and is deferred for future study. Here, we presented results for two important management variables: the number of days suitable for conducting prescribed burning in spring, and the number of days on which fire could burn in summer.

During warmer-drier years there were more days on which fires could burn and the frequency of low moisture contents was higher than in cooler-wetter years. If Australia's climate continues to warm and dry, then our results predict that there will be greater potential for more frequent and more severe fires than under current climate. In warmer-drier years this occurs through an increase in the upper limit of fire days per season and through increased frequency of low moisture contents. Although there was a weak correlation between the number of burning days in spring and rainfall and temperature, our results for prescribed burning were dominated by variability. Thus it is not clear from analysis of simple climate variables such as mean temperature and seasonal rainfall what future changes can be expected.

The results presented here for summer are similar to those found in studies that modelled fire danger (e.g. Hennessy 2005). However, the data sets generated in this study provide the basis for a more detailed investigation of fuel moisture, e.g. burning conditions, and examination of the variation of physical processes, particularly drying after rain.

The analysis presented here is only a very simple overview of the climate and fuel moisture data set created. Further work will be required to look more deeply at the relationships between climate and fuel moisture. This analysis can also be extended by combining the fuel moisture results with wind speed to predict fire danger.

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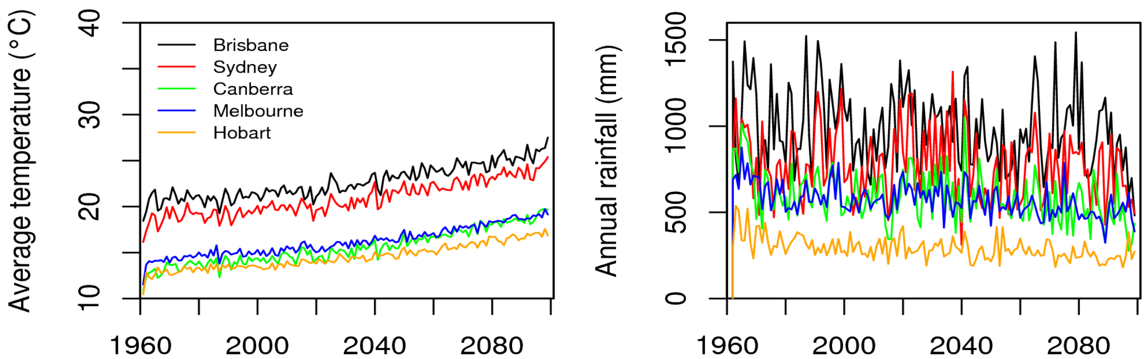

Figure 1: Annual mean temperature and rainfall for five Australian cities simulated using the CCAM model.

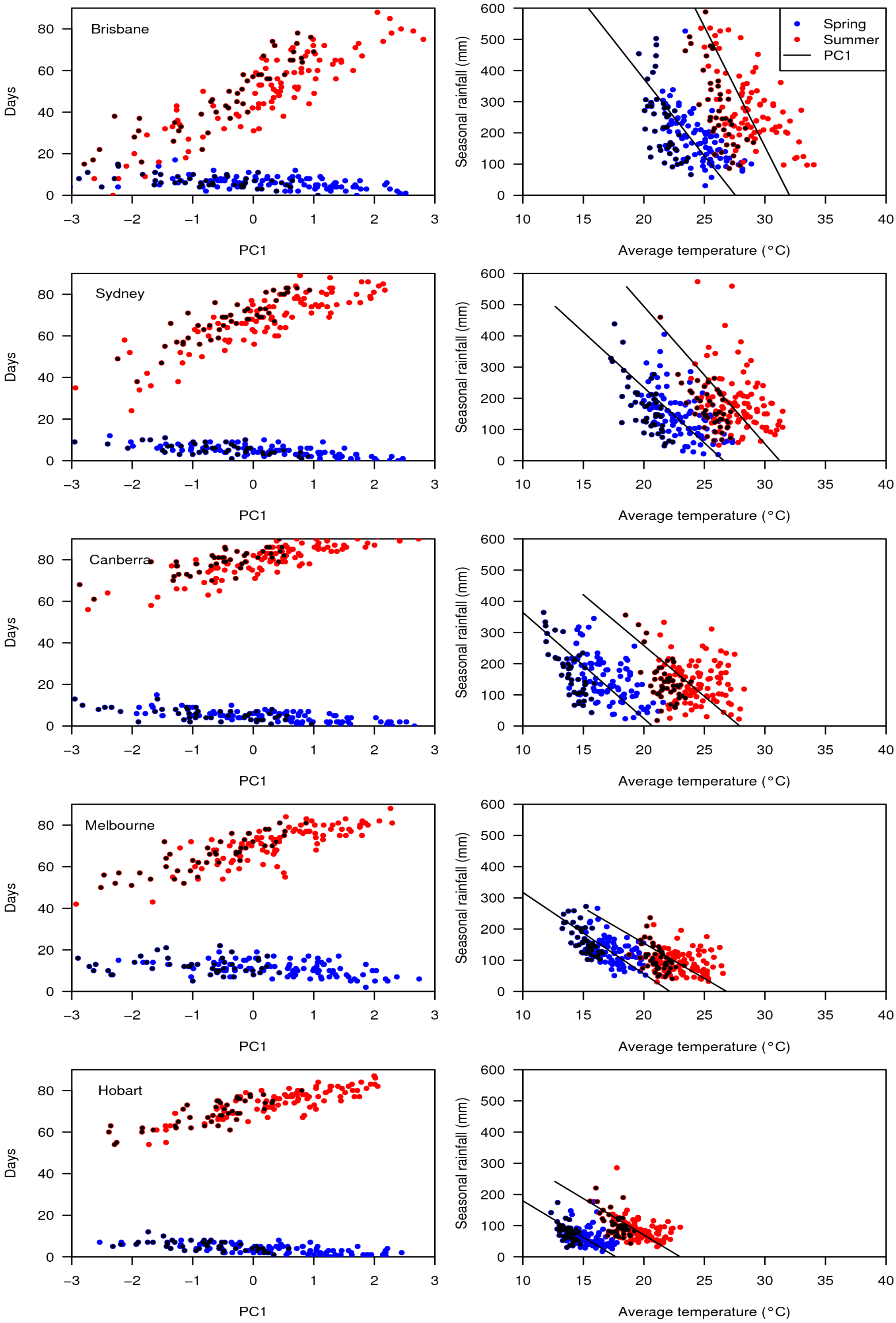

Figure 2: Left) Number of spring burning and summer fire days. Negative PC1 is cool-wet, positive is warm-dry. Black dots are simulated current climate (1961-2008), coloured dots are future climate (2009-2100). Right) Seasonal mean temperature and rainfall. Lines are PC1 axis.

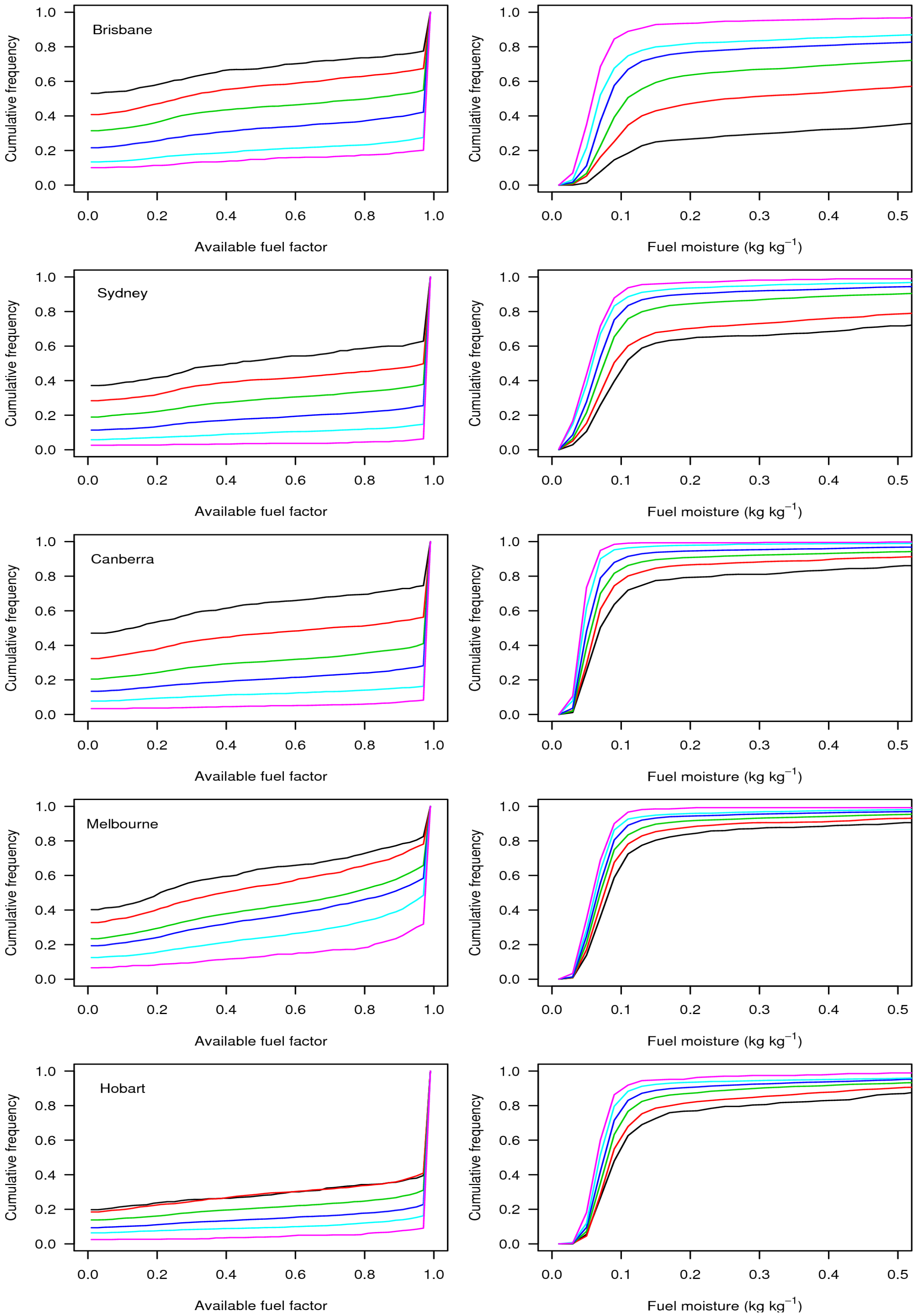

Figure 3: Left) Available fuel factor cumulative frequency histograms in spring for binned PC1 values. Black is cool-wet, pink is warm-dry, bins are 1 unit wide, centers from -2.5, to +2.5. Right) As left for surface fuel moisture in summer.