Climate change impacts on fire-weather in south-east Australia

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EXECUTIVE SUMMARY

Fire risk is influenced by a number of factors – including fuels, terrain, land management, suppression and weather. This study assesses potential changes to one of these factors, fire-weather risk, associated with climate change. Fire-weather risk relates to how a combination of weather variables influences the risk of a fire starting or its rate of spread, intensity or difficulty of suppression. The study is based in south-east Australia, an area projected to become hotter and drier under climate change.

The study uses fire danger indices, such as the Forest Fire Danger Index (FFDI) and Grassland Fire Danger Index (GFDI), to provide an indication of fire risk based on various combinations of weather variables. These variables include daily temperature, precipitation, relative humidity and wind-speed.

Fire danger indices are calculated for historical weather records from 1974-2003 for sites in New South Wales, the Australian Capital Territory, Victoria and Tasmania. Two climate models are then used to generate climate change scenarios for 2020 and 2050, including changes in average climate and daily weather variability. Fire danger indices are then calculated for 2020 and 2050.

This study is a significant methodological improvement on earlier fire risk assessments in Australia. It avoids biases from:

- using raw daily climate model data that may not be representative of observed climate, or
- inadequate assessment of changes in extreme weather events through failure to take sufficient account of likely changes in daily weather variability.

A key finding of this study is that an increase in fire-weather risk is likely at most sites in 2020 and 2050, including the average number of days when the FFDI rating is very high or extreme. The combined frequencies of days with very high and extreme FFDI ratings are likely to increase 4-25% by 2020 and 15-70% by 2050. For example, the FFDI results indicate that Canberra is likely to have an annual average of 25.6-28.6 very high or extreme fire danger days by 2020 and 27.9-38.3 days by 2050, compared to a present average of 23.1 days. The increase in fire-weather risk is generally largest inland. Tasmania is likely to be relatively unaffected.

The study also indicates that the window available for prescribed burning may shift and narrow. It is likely that higher fire-weather risk in spring, summer and autumn will increasingly shift periods suitable for prescribed burning toward winter.

A number of uncertainties remain when assessing potential changes to fire-weather risk associated with climate change. These uncertainties relate to:

- the quality of data for some weather variables
- the possibility of different results arising from the use of other climate models
- changes in seasonal indicators used for fire preparedness planning
- changes in rainfall thresholds required to control fires
- changes in ignition and fuel load
- changes in El Niño-Southern Oscillation events under climate change.

TECHNICAL SUMMARY

Since 1950, rainfall has decreased in south-east Australia, droughts have become more severe and the number of extremely hot days has risen. The effect of these changes on fire frequency and intensity is not evident, although it is clear that hotter and drier years have greater fire risk. Climate change projections indicate that the south-east is likely to become hotter and drier in future. The aim of this study is to assess potential changes in fire-weather risk associated with future climate change, due to the enhanced greenhouse effect. Fire weather is only one of the important factors determining fire risk and fire behaviour – fuels, terrain and suppression are also critical, but these have not been assessed in this report. This is just a first step toward better informing fire management agencies and researchers about climate change risks. Ongoing engagement between scientists and fire management agencies is needed to maximise the value of this assessment.

The weather variables required for this analysis were daily maximum temperature, precipitation, 3 pm relative humidity and wind-speed. For the 30-year period 1974-2003, data for all four weather variables were available at 17 sites in New South Wales (NSW), the Australian Capital Territory (ACT), Victoria and Tasmania, namely:

- NSW: Coffs Harbour, Cobar, Williamtown, Richmond, Sydney, Nowra, Wagga, Bourke, Cabramurra
- Victoria: Mildura, Melbourne, Laverton, Sale, Bendigo
- ACT: Canberra
- Tasmania: Hobart, Launceston

The maximum daily Forest Fire Danger Index (FFDI) and Grassland Fire Danger Index (GFDI) were calculated at each site for “present” conditions (1974-2003). The FFDI and GFDI are used operationally to monitor fire risk, schedule prescribed burning and declare Total Fire Ban days. Climate change scenarios for 2020 and 2050 were generated from two CSIRO climate models. These scenarios included changes in average climate and daily weather variability, and were applied to observed daily weather data. This method is unique in Australian fire risk assessments, and perhaps internationally. It avoids the limitations of two other methods commonly used: (1) biases often found when using raw climate model data that include changes in daily variability, and (2) inadequate assessment of changes in extreme weather events when applying changes in monthly-average climate to observed daily data. Our method includes changes in daily variability without the biases from raw climate model data, giving more reliable fire risk projections.

The choice of climate simulations for this study was constrained by a number of factors; (1) models that perform well over south-eastern Australia, (2) availability of simulated data with fine resolution (grid-spacing of 50 km or less), and (3) availability of simulated daily weather data from which to compute changes in daily variability. An assessment of the performance of 20 models over south-eastern Australia showed that 13 adequately reproduced observed average patterns of temperature, rainfall and pressure. Ten of these were global climate models with a grid-spacing of 200-400 km and monthly data, but only three had a grid-spacing of about 50 km and daily data. One of the 50 km simulations was based on a CSIRO model (DARLAM) that has been superseded, so the other two 50 km simulations (CCAM) were used. CCAM is a global atmosphere-only model with fine resolution over Australia that can be driven by boundary conditions from a global climate model (including ocean, atmosphere, ice and land). One CCAM simulation was driven by CSIRO's Mark2 global climate model and the other was driven by CSIRO's Mark 3 global climate model, henceforth called CCAM (Mark2) and CCAM (Mark3). Both perform well over south-east Australia, although CCAM (Mark 2) has a better simulation of average temperature. On this basis, slightly more confidence could be placed in results from CCAM (Mark2). Their climate projections are considered independent. Regional climate change patterns from each model were scaled to include the full range of IPCC SRES scenarios of greenhouse gas and aerosol emissions, and the full range of IPCC uncertainty in climate sensitivity to these emissions (Appendix 1).

The climate change scenarios were applied to observed daily weather data at 17 sites. The FFDI and GFDI results were calculated in three ways.

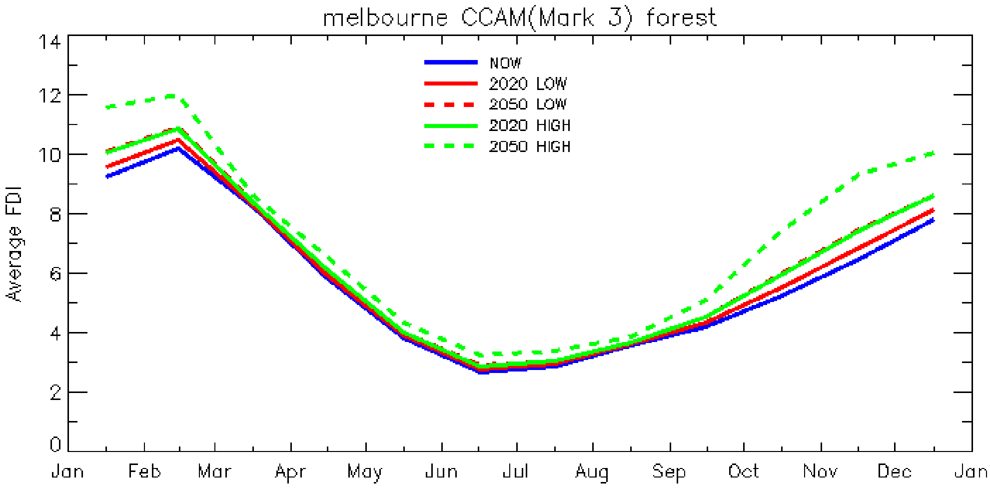
- Annual-average cumulative FFDI and GFDI, denoted ΣFFDI and ΣGFDI
- Monthly-average FFDI and GFDI
- Daily-average FFDI and GFDI

The "present" average ΣFFDI in inland areas is around 3000-5000, while southern and coastal areas have values around 1700-2600. For CCAM (Mark2), the values rise by around 2-10% by 2020 and 5-25% by 2050. For CCAM (Mark3), the values rise by around 3-10% by 2020 and 8-30% by 2050.

Annual-average ∑FFDI at 17 sites for present (1974-2003) conditions, and percentage changes for 2020 and 2050, for low and high rates of global warming.

Site	Present	CCAM (Mark2)				CCAM (Mark3)			
		2020 low %	2020 high %	2050 low %	2050 high %	2020 low %	2020 high %	2050 low %	2050 high %
Canberra	2913	4	8	10	26	4	10	11	29
Bourke	5869	4	9	9	25	3	7	7	19
Cabramurra	501	5	10	10	26	7	14	15	40
Cobar	5818	4	10	10	26	3	8	8	22
Coffs Harbour	2002	2	5	5	12	3	6	6	15
Nowra	2507	1	4	4	13	2	6	6	18
Richmond	3049	4	8	8	20	4	8	8	21
Sydney	2158	2	4	5	12	3	7	7	19
Wagga	4047	4	8	9	23	4	9	9	25
Williamtown	2641	2	5	5	13	3	7	7	18
Bendigo	2854	3	8	8	22	3	8	8	23
Laverton	2456	3	8	8	21	4	9	9	24
Melbourne	2121	3	8	8	21	3	8	8	22
Mildura	5898	3	7	7	17	3	8	8	21
Sale	2207	3	8	8	21	4	8	8	23
Hobart	1723	0	0	0	-1	0	1	1	2
Launceston	1677	1	3	3	8	3	6	6	17

The monthly-average FFDI results show that most sites currently have the highest fire danger in spring and summer (blue curves in plot below). A spring peak is distinctive for coastal NSW sites, whereas the summer peak is typical of southern and inland sites. In 2020 and 2050, the curves move upward, indicating higher fire danger, particularly in spring, summer and autumn. Periods suitable for prescribed (control) burning are likely to move toward winter.



Monthly-average FFDI at Melbourne for “now” (1974-2003), 2020 and 2050, based on the CCAM (Mark3) climate change scenarios.

The daily-average frequency distributions of FFDI have five intensity categories: low (less than 5), moderate (5-12), high (13-25), very high (25-49) and extreme (at least 50). At all sites, except Hobart, Launceston and Cabramurra, there is an increase in the frequency of very high and extreme days by 2020 and 2050. These are the categories of most interest to fire management agencies. By 2020, the combined frequencies of very high and extreme FFDI generally increase 4-20% for CCAM (Mark2) and 6-25% for CCAM (Mark3). By 2050, the increases are generally 15-55% for CCAM (Mark2) and 20-70% for CCAM (Mark3).

Average number of days when the FFDI rating is “very high” or “extreme” under present conditions (1974-2003) for the years 2020 and 2050.

Site	Present	CCAM (Mark2)				CCAM (Mark3)			
		2020 low	2020 high	2050 low	2050 high	2020 low	2020 high	2050 low	2050 high
Canberra	23.1	25.6	27.5	27.9	36.0	26.0	28.6	28.9	38.3
Bourke	69.5	75.2	83.3	84.0	106.5	73.9	80.3	80.6	96.2
Cabramurra	0.3	0.3	0.4	0.4	0.7	0.4	0.4	0.5	1.0
Cobar	81.8	87.9	96.2	96.6	118.3	86.6	92.8	93.0	108.6
Coffs Harbour	4.4	4.7	5.1	5.1	6.3	4.7	5.6	5.6	7.6
Nowra	13.4	13.9	14.7	14.8	17.5	14.2	15.6	15.6	19.9
Richmond	11.5	12.9	14.0	14.1	17.5	13.1	14.3	14.4	19.1
Sydney	8.7	9.2	9.8	9.8	11.8	9.5	11.1	11.3	15.2
Wagga	49.6	52.7	57.3	57.6	71.5	52.8	57.4	57.7	71.9
Williamtown	16.4	17.2	18.2	18.4	20.9	17.3	19.4	19.4	23.6
Bendigo	17.8	19.5	21.3	21.4	27.3	19.7	21.9	22.0	29.8
Laverton	15.5	16.4	17.3	17.3	21.2	16.6	17.8	17.8	22.3
Melbourne	9.0	9.8	10.7	10.8	13.9	9.8	11.1	11.2	14.7
Mildura	79.5	83.9	89.5	89.9	104.8	84.6	90.7	90.9	107.3
Sale	8.7	9.3	10.0	10.1	12.1	9.6	10.7	10.8	14.0
Hobart	3.4	3.4	3.4	3.4	3.4	3.4	3.5	3.5	3.5
Launceston	1.5	1.5	1.5	1.6	2.0	1.6	1.9	1.9	3.1

Changes in the frequencies of extreme FFDI days are generally largest inland, e.g. at Bourke, Cobar, Mildura and Wagga. By 2020, the increases are generally 10-30% for CCAM (Mark2) and 15-40% for CCAM (Mark3). By 2050, the increases are generally 20-80% for CCAM (Mark2) and 40-120% for CCAM (Mark3). At many sites, there is a doubling (or greater) of the number of extreme days by 2050 for the high scenario. Tasmania is relatively unaffected. In Hobart, the rise in temperature is offset by a rise in humidity.

The magnitude of the grassland fire danger index is always higher than the FFDI since the GFDI is more strongly influenced by wind-speed and we have assumed a worst-case scenario of 100% curing. By 2020, the number of very high or extreme GFDI days increases by around 0-15% for CCAM (Mark2) and 5-20% for CCAM (Mark3). By 2050, the increases are generally 5-30% for CCAM (Mark2) and 15-40% for CCAM (Mark3).

Average number of days when the GFDI rating is “very high” or “extreme” under present conditions (1974-2003) and for the years 2020 and 2050.

Site	Present	CCAM (Mark2)				CCAM (Mark3)			
		2020 low	2020 high	2050 low	2050 high	2020 low	2020 high	2050 low	2050 high
Canberra	96.8	100.3	103.7	104.0	113.1	103.5	110.3	110.6	129.0
Bourke	90.6	97.5	102.9	103.3	117.9	97.7	102.7	103.0	117.0
Cabramurra	11.6	11.6	11.8	11.8	12.6	12.5	13.8	13.9	18.6
Cobar	112.8	124.1	129.0	129.4	146.6	124.0	129.5	130.1	148.1
Coffs Harbour	86.4	99.9	101.8	101.8	109.1	101.5	105.2	105.6	117.7
Nowra	71.7	80.3	81.7	81.8	86.3	83.5	88.5	88.9	104.0
Richmond	40.4	44.1	44.8	44.8	47.1	45.3	47.4	47.5	55.1
Sydney	116.2	117.6	120.0	120.1	126.8	122.1	129.3	129.7	153.5
Wagga	104.6	110.7	114.4	114.4	123.5	112.5	118.7	119.0	134.2
Williamtown	123.1	132.2	134.9	135.1	144.1	135.0	141.8	142.5	162.9
Bendigo	61.1	63.6	65.8	65.9	72.4	65.0	69.5	69.7	81.7
Laverton	110.1	109.4	111.7	111.9	118.6	111.8	117.4	117.9	131.7
Melbourne	38.7	41.2	41.2	42.2	45.7	42.3	45.0	45.2	54.5
Mildura	146.7	149.1	153.6	153.9	165.6	150.6	157.6	157.0	174.6
Sale	95.4	102.5	104.0	104.1	109.3	104.9	110.2	110.3	124.2
Hobart	67.5	67.5	67.2	67.2	66.1	68.1	68.8	69.0	71.5
Launceston	73.3	73.4	72.3	72.3	69.4	78.5	85.0	85.5	102.8

By 2020, the number of extreme GFDI days increases by around 5-20% for CCAM (Mark2) and 10-30% for CCAM (Mark3). By 2050, the increases are generally 10-30% for CCAM (Mark2) and 30-80% for CCAM (Mark3).

A number of uncertainties remain:

- Quality of observed daily wind and humidity data at most sites in Australia
- The effect of scenarios based on other climate models
- Assessment of changes in the range (and sensitivity) of seasonal indicators used by fire management agencies for fire preparedness planning.
- Changes in rainfall thresholds required to control fires
- Changes in ignition (natural and anthropogenic)
- Changes in fuel load, allowing for carbon dioxide fertilization on vegetation
- Potential impacts on biodiversity, water yield and quality from fire affected catchments, forestry, greenhouse gas emissions, emergency management and insurance.

Priorities for further research include:

- Testing and rehabilitation of observed humidity and wind data
- Creation of climate change scenarios from other models
- Fine scale fire modelling that captures vegetation and terrain features and fire management
- Hydrological and ecological modelling to assess impacts on water and biodiversity
- Using satellite remote sensing to monitor the extent and nature of fire, recovery of vegetation after fire, and greenhouse gas emissions from fire.

1 Introduction

Since 1950, Australia has warmed by 0.85°C, rainfall has decreased in the south-east, droughts have become hotter (Nicholls, 2003) and the number of extremely hot days has risen (Nicholls and Collins, in press). The effect of these changes on fire frequency and intensity in the south-east is not clearly evident, partly due to confounding factors such as fire management and arsonists. However, it is clear that hotter and drier years have greater fire risk (BTE, 2001). Climate change projections indicate that Victoria and NSW are likely to become hotter and drier in future (CSIRO, 2001; Hennessy *et al*,, 2004; Suppiah *et al*, 2004), while Tasmania is likely to become warmer and wetter (McInnes *et al*., 2004). The aim of this study is to assess potential changes in fire-weather risk associated with future climate change, due to the enhanced greenhouse effect. It represents a resource for ongoing engagement with fire management agencies to plan for the impacts of climate change. However, the report is not intended to provide management recommendations to agencies.

Bushfires have been part of Australia's environment for millions of years. Our natural ecosystems have evolved with fire, and our landscapes and their biological diversity have been shaped by both historical and recent patterns of fire (Cary, 2002). South-eastern Australia has highest risk in spring, summer and autumn (Figure 1). This region has the reputation of being one of the three most fire-prone areas in the world, along with southern California and southern France.

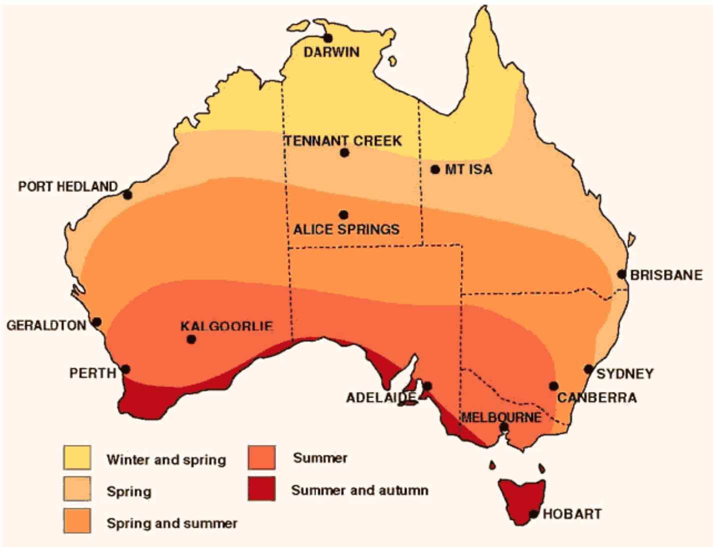


Figure 1: Seasonal pattern of fire danger. http://www.bom.gov.au/climate/c20thc/fire.shtml

Very little of the Australian continent is free from fires - scrub-fires may sweep even the arid regions in years when good wet season rains are followed by a long dry spell. In the spring of 1974, 15 percent of the land area of Australia burned after prolific growth during the preceding wet summer dried off and ignited. The Black Friday fires in Victoria (1939), the 1967 fires in Tasmania, and the Ash Wednesday fires in Victoria and South Australia (1983) have each killed more than 60 people. Throughout the 20th Century, many other fires have claimed lives, destroyed people's homes and livelihoods, and reduced thousands of hectares of forest to charcoal and ash. From 1960-2001, there were 224 fire-related deaths, 4505 injuries and $2475 million in damages (McMichael *et al.*, 2003). More than half the fire-related deaths, injuries and costs were in Victoria. The insured costs of fire damage from 1967-2005 are shown in Table 1. Many of these fires occurred during droughts associated with El Niño events. The most costly fires occurred in 1983 ($138 million) and 2003 ($342 million). Damage to plantation timber was a significant component of the costs in 1983. There are also periods where Australia has not been affected by any large bushfires (e.g. 1970-76, 1998-2000), mainly due to the wetter La Niña conditions.

Table 1: Insured costs of fire damage from 1967-2005 (http://www.idro.com.au/disaster_list)

Date	Location	Original cost* $m
Feb 1967	Hobart TAS	14
Feb 1977	Western VIC	9
Feb 1980	Adelaide Hills SA	13
Feb 1983	VIC	138
Feb 1983	SA	38
Sep 1984	NSW	25
Feb 1987	Southern TAS	7
Jan 1990	VIC	10
Oct 1991	Central coast NSW	12
Jan 1994	Sydney NSW	59
Jan 1997	Ferny Creek VIC	10
Dec 1997	Sydney NSW	3
Dec 2001	Sydney NSW	69
Oct 2002	Sydney NSW	19
Jan 2003	Northeast VIC Southeast NSW	12
Jan 2003	Canberra ACT	342
Jan 2005	Eyre Peninsula SA	27

* cost at time of event, not adjusted for inflation.

1.1 Previous assessments of climate change impacts on fire risk

Global warming is likely to increase fire frequency and severity. Various overseas studies have shown this, e.g. Stocks *et al* (1998), Goldammer and Price (1998), Wotton *et al* (2003), Brown *et al* (2004), Pearce *et al* (2005). In Australia, the McArthur Mark 5 Forest Fire Danger Index (FFDI) is used operationally by weather forecasters and fire services throughout eastern Australia to determine fire hazard and declare Total Fire Ban days. The FFDI has been closely related to the probability of asset destruction in the Sydney region (Bradstock and Gill, 2001) (Figure 2). Beer *et al* (1988) and Beer and Williams (1995) assessed the potential change in fire danger using the FFDI and various climate change scenarios. Beer and Williams (1995) found that the annual accumulated FFDI increased by at least 10% for a doubling of carbon dioxide concentration over most major forest fire zones in southern and eastern Australia.

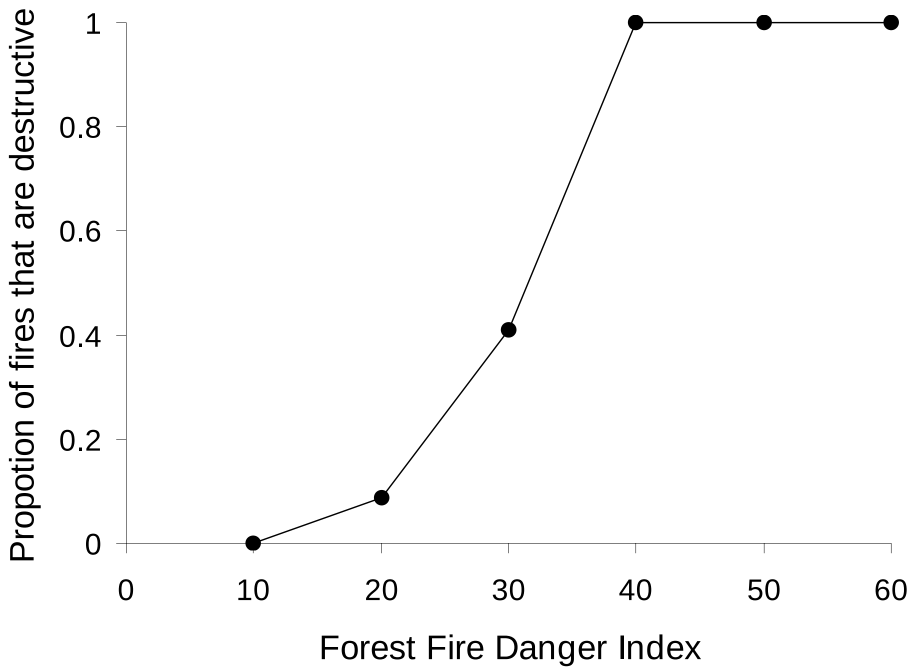


Figure 2: Trend in the proportion of unplanned fires in Sydney which resulted in house destruction between 1954 and 1995, in relation to FFDI (Source: Bradstock and Gill, 2001).

Williams *et al* (2001) used simulated weather data from the CSIRO9 climate model for present and enhanced greenhouse conditions (circa 2050) to assess changes in the daily FFDI at eight Australian sites: Katanning (WA), Normanton (northern Qld), Miles (southeast Qld), Alice Springs (NT), Hobart (Tas), Mildura and Sale (Vic). An increase in fire danger was simulated at all sites.

Cary (2002) used simulated weather data from the CSIRO regional climate model (DARLAM) for present and enhanced greenhouse conditions over the ACT. Changes by the year 2070 were:

- 0.6 to 3.4^{o}C warmer
- 1-2% lower relative humidity
- 0-25% less rain in Jan-Oct, 8-10% more rain in Nov-Dec
- No change in wind-speed.

These changes were applied to daily weather data and fed into the ANU FIRESCAPE model to assess changes in the FFDI. The results were

- 5-20% increase in annual accumulated FFDI
- 12-70% decrease in years between fires at same location
- 7-25% increase in fire-line intensity.

FIRESCAPE is also being tested over southwest Tasmania, central Australia and the greater Sydney basin. Since it runs at 1 km resolution, it requires detailed topographic and vegetation information, and significant computer resources.

2 Methodology for an updated fire risk assessment in south-east Australia

There are various ways of using climate model information in fire risk models. These include:

1. Generate daily weather data using a climate change model for present and enhanced greenhouse conditions, then use these data as input to a fire risk model (e.g. Beer and Williams, 1995; Williams *et al,,* 2001). While this has the advantage of capturing changes in relationships between weather variables, and changes in daily weather variability, it has the disadvantage of being biased by errors in the simulated baseline climate, i.e. the simulation may be too warm/cold or wet/dry on average. For example, Cary (2002) found that some errors in the simulated baseline climate were as large as the changes in climate projected due to a doubling of carbon dioxide. While corrections can be applied, residual errors remain (especially for extreme fire danger events), and the spatial resolution is very coarse (about 300 km between data points).
2. Compute the changes in monthly average weather variables from a climate model, then apply these changes to observed daily weather data, which are then input to a fire risk model (e.g. Cary, 2002). This has the advantage of avoiding biases that exist in the simulation of baseline conditions, while having the disadvantages of assuming (i) that existing relationships between weather variables will be maintained in future, and (ii) there will be no change in daily weather variability. These disadvantages are generally not considered serious. Another disadvantage is the limited availability of sites with daily records of the four key weather variables, i.e. temperature, rainfall, relative humidity and wind-speed.
3. Compute changes in daily weather variability from a climate model, then apply these changes to observed daily weather data. This avoids biases in the simulated baseline climate and avoids disadvantages (i) and (ii). Including changes in daily weather variability and the behaviour of extreme events are obviously important for fire-weather risk.

Method 3 was used in the present study. It is unique in Australian fire risk assessments. There were four main steps, as described below.

2.1 Select sites with high quality observed daily weather data

The weather variables required for this analysis were daily maximum temperature, precipitation, minimum (3 pm) relative humidity and maximum wind-speed. A 30-year period centred on 1990 was needed since climate change projections are relative to 1990. The Bureau of Meteorology has developed high quality data sets for daily temperature and rainfall (Haylock and Nicholls, 2000; Collins *et al.*, 2000). Creation of a high quality dataset for humidity is being undertaken by the Bureau of Meteorology, sponsored by the Bushfire CRC. Preliminary humidity data for selected sites were made available for the present study. The quality of the humidity data is acceptable at most sites. However, at Cabramurra, there is only one humidity observation per day (at 9 am) in much of the record, and since humidity is quite high early in the morning, this may underestimate fire danger results at that site. Due to resource limitations, wind-speed data have not been homogenized, so there are some data problems due to changes in instrumentation and observer practices. While the wind data are usable, they may introduce errors within the analysis. For example, at Richmond, some wind data are missing in the 1970s. Also, at Melbourne, the wind-speed dropped after 2000 due to a shift in instrumentation. However, temperature and humidity are the most important drivers of fire-weather (Beer and Williams, 1995; Williams *et al.*, 2001).

For the period 1974-2003, data for all four weather variables were available at 17 sites (Figure 3):

- NSW: Coffs Harbour, Cobar, Williamtown, Richmond, Sydney, Nowra, Wagga, Bourke, Cabramurra
- Victoria: Mildura, Melbourne, Laverton, Sale, Bendigo
- ACT: Canberra
- Tasmania: Hobart, Launceston

Figure 3: Locations of the 17 sites used in this study.

2.2 Derive daily soil moisture, drought and fire danger indicators for present conditions

At each site, observed weather data were used to compute daily values of the Mount Soil Dryness Index (SDI), Keetch Byram Drought Index (KBDI), FFDI and Grassland Fire Danger Index (GFDI). The average number of days exceeding low, medium, high, very high and extreme levels was calculated.

In preparation for the climate change scenarios, observed frequency distributions of the four weather variables were computed for each of the 12 calendar months. For each day in the 30 years, the weather variables were assigned to one of ten deciles by comparing the value for that day with the frequency distribution for that month.

Deciles are defined as

- Decile 1: the lowest 10% of values
- Decile 2: values in the lowest 10-20%
- Decile 3: values in the lowest 20-30%
- Decile 4: values in the lowest 30-40%
- Decile 5: values in the lowest 40-50%
- Decile 6: values in the highest 40-50%
- Decile 7: values in the highest 30-40%
- Decile 8: values in the highest 20-30%
- Decile 9: values in the highest 10-20%
- Decile 10: the highest 10% of values.

In previous fire risk assessments, where changes in mean monthly climate have been applied to observed daily weather data (e.g. Cary, 2002), each decile has been changed by the same amount. This assumes no change in future weather variability, so the shape of each monthly frequency distribution remains unchanged while the mean increases or decreases (Figure 4a).

In this study, each decile has been changed by different amounts, according to changes in the mean and variability simulated by two climate models, so the shape of each monthly frequency distribution changes (Figure 4c). This improves the reliability of fire-weather projections since changes in extremely high temperature and wind-speed, and extremely low humidity, are critical for fire risk.

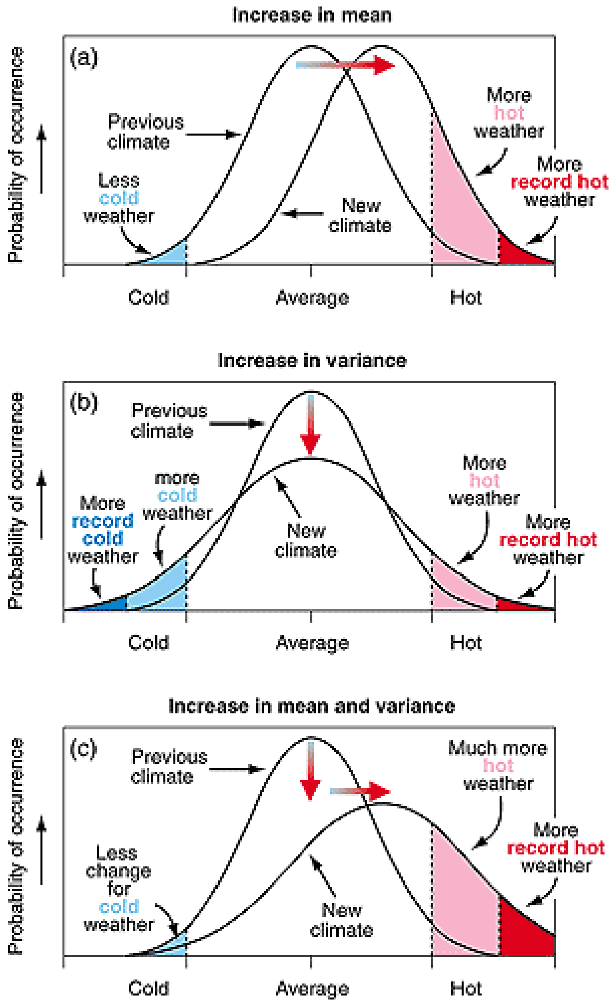


Figure 4: The effects on extreme temperatures when (a) the mean increases with no change in variance, (b) the variance increases with no change in the mean, and (c) when both the mean and variance increase, leading to more record hot weather. Source IPCC (2001).

2.3 Create climate change scenarios for each decile

The choice of climate simulations for this study was constrained by a number of factors: (1) models that perform well over south-eastern Australia, (2) availability of simulated data with grid-spacing of 50 km or less, and (3) availability of simulated daily weather data from which to compute changes in daily variability. An assessment of the performance of 20 climate models over south-eastern Australia showed that 13 adequately reproduced observed average patterns of temperature, rainfall and pressure (McInnes *et al*., 2005). Ten of these were global climate models with a grid-spacing of 200-400 km and monthly data, but only three had a grid-spacing of about 50 km and daily data. One of the 50 km simulations was based on a CSIRO model (DARLAM) that has been superseded, so the other two 50 km simulations (CCAM) were used.

CCAM is a global atmosphere-only model, developed by CSIRO, that can be driven by boundary conditions from a global climate model (including ocean, atmosphere, ice and land) (McGregor and Dix, 2001). At 50 km resolution, CCAM has a better representation of climate and topographic processes than most global climate models. One CCAM simulation was driven by CSIRO's Mark2 climate model and the other was driven by CSIRO's Mark 3 climate model, henceforth called CCAM (Mark2) and CCAM (Mark3). Both perform well over south-east Australia, although CCAM (Mark 2) has a better simulation of average temperature. Hence, slightly more confidence can be placed in results from CCAM (Mark2). The ability of the models to reproduce observed wind and humidity has not been tested, although validation of the pressure patterns implies that wind patterns are well simulated. Their climate projections are considered independent since the Mark 2 and Mark 3 models have different parameterisations of physical processes. Regional climate change patterns from each model were expressed as a change per degree of global warming. This allows the results to be linearly scaled for any future year using the IPCC (2001) global warming estimates (Mitchell, 2003), which include the full range of IPCC SRES (2000) scenarios of greenhouse gas and aerosol emissions, and the full range of IPCC (2001) uncertainty in climate sensitivity to these emissions (Whetton, 2001; Appendix 1).

At each of the 17 sites in both simulations,

- "Present" deciles were calculated for daily maximum temperature, rainfall, wind-speed and relative humidity, for each calendar month in a 30-year period centred on 1990.
- For each year in the period 1962-2100, deciles were calculated for each climate variable for each month, using a 3-year window centred on the year of interest
- For each year in the period 1962-2100, the change in each decile relative to the "present" values was calculated for each month.
- For each year in the period 1962-2100, the annual global mean warming was calculated.
- We assumed that there is a linear relationship between annual global mean warming and regional climate change (Whetton, 2001; Mitchell, 2003; Whetton *et al*, in prep.). For each year in the period 1962-2100, the regional decile changes were regressed against the global warming values. This gave a decile change per degree of global warming for each variable.
- Regional projections are presented as low-high ranges (probabilities are not available). The low regional projection is based on a low global warming projection (low emission scenario with low climate sensitivity), while the high regional projection is based on a high global warming projection (high emission scenario with high climate sensitivity) – see Appendix 1. Regional projections for 2020 and 2050 were computed by multiplying the regional decile changes per degree of global warming by the IPCC low-high global warming values for the years 2020 and 2050, namely 0.37-0.85^{o}C by 2020 and 0.88-2.24^{o}C by 2050.

Rather than showing climate change scenarios for each site, Figure 5 shows examples of monthly climate change scenarios for the four capital cities (Canberra, Sydney, Melbourne and Hobart).

Canberra

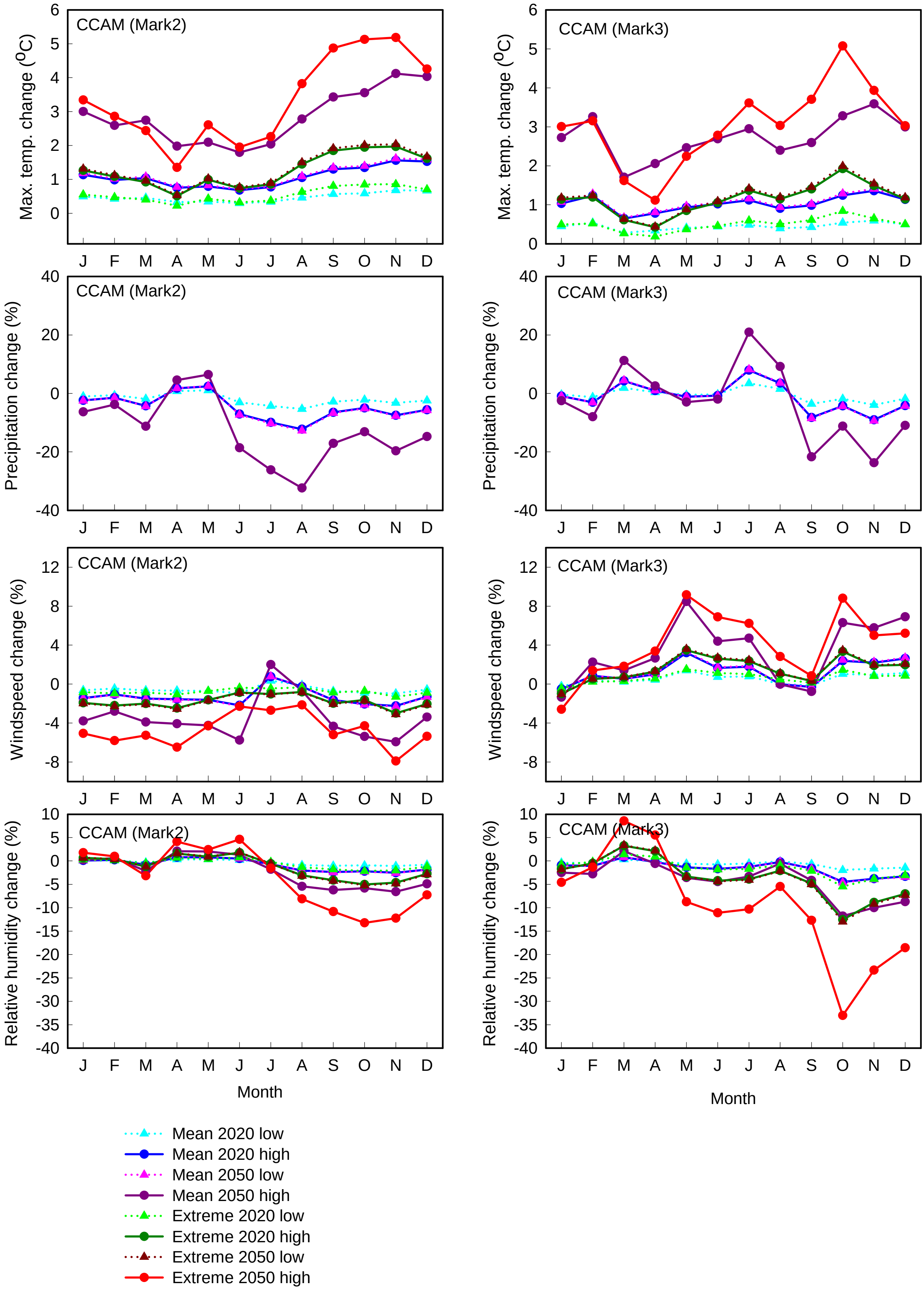


Figure 5a: Climate change scenarios for Canberra in 2020 and 2050, relative to 1990. Mean changes in maximum temperature, rainfall, relative humidity and wind-speed summarise the changes across deciles 1 to 10. Extreme changes represent decile 10 for maximum temperature and wind-speed, and decile 1 for relative humidity.

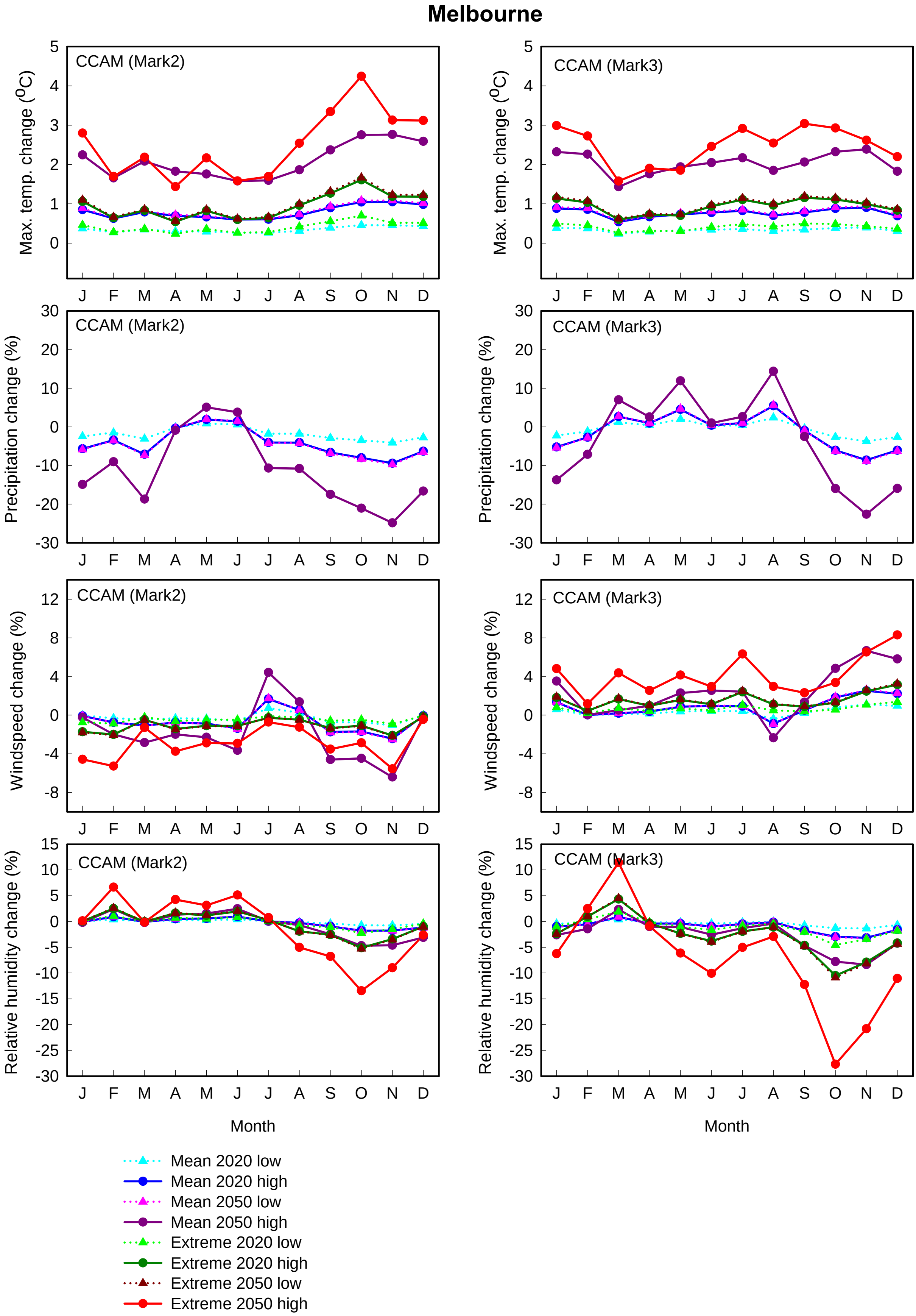


Figure 5b: Climate change scenarios for Melbourne in 2020 and 2050, relative to 1990. Mean changes in maximum temperature, rainfall, relative humidity and wind-speed summarise the changes across deciles 1 to 10. Extreme changes represent decile 10 for maximum temperature and wind-speed, and decile 1 for relative humidity.

Sydney

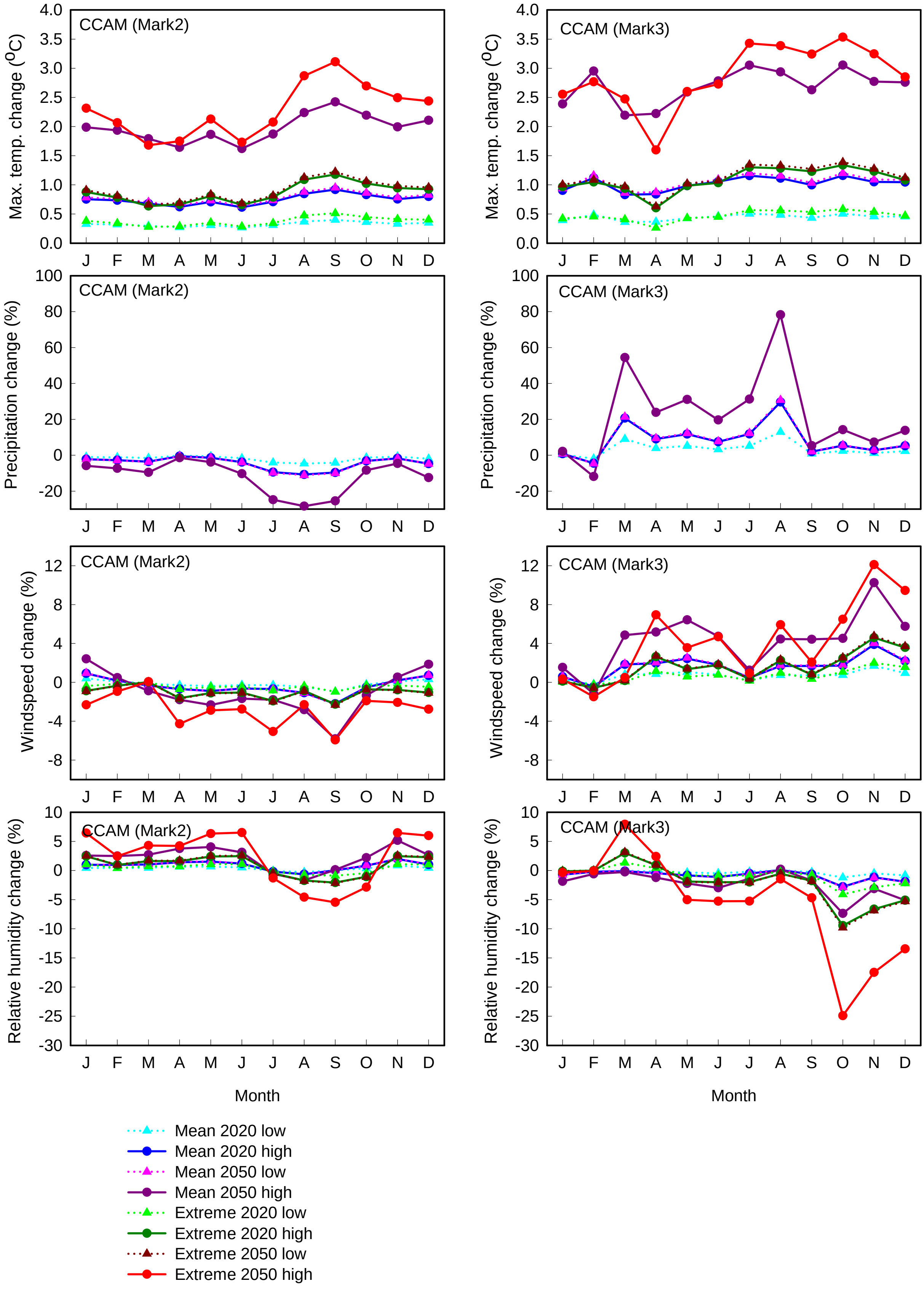


Figure 5c: Climate change scenarios for Sydney in 2020 and 2050, relative to 1990. Mean changes in maximum temperature, rainfall, relative humidity and wind-speed summarise the changes across deciles 1 to 10. Extreme changes represent decile 10 for maximum temperature and wind-speed, and decile 1 for relative humidity.

Hobart

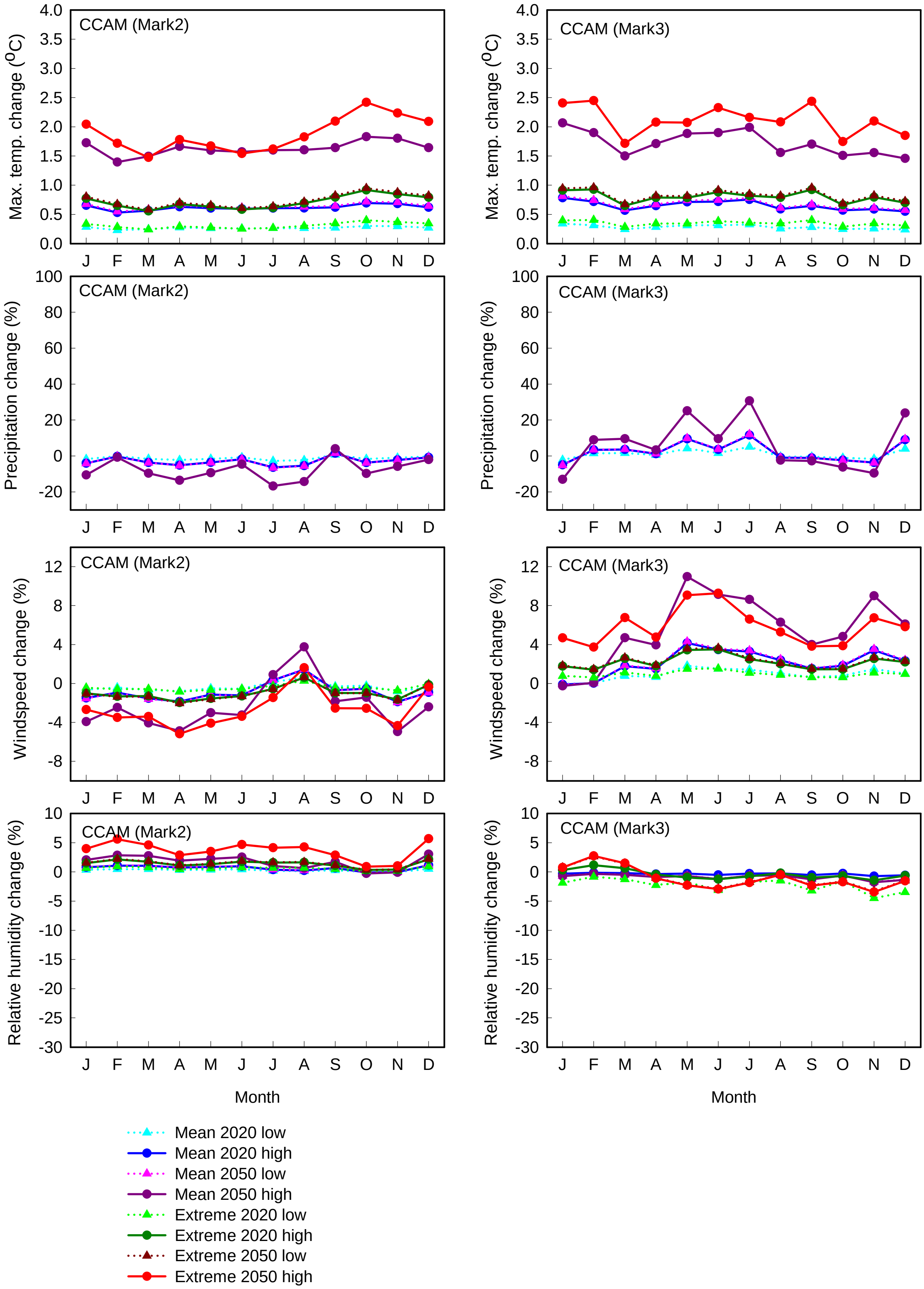


Figure 5d: Climate change scenarios for Hobart in 2020 and 2050, relative to 1990. Mean changes in maximum temperature, rainfall, relative humidity and wind-speed summarise the changes across deciles 1 to 10. Extreme changes represent decile 10 for maximum temperature and wind-speed, and decile 1 for relative humidity.

Some brief observations can be made from the figures above:

- The mean warming is around 0.5-1.5^oC by 2020 and around 1.5-3.0^oC by 2050
- Mean rainfall tends to increase in autumn and decrease in spring-summer in Canberra and Melbourne
- Mean rainfall tends to increase in autumn-winter in Sydney and Hobart in CCAM (Mark3) but decrease in CCAM (Mark2)
- Mean wind-speed tends to decrease throughout the year at each site in CCAM (Mark2) but increase in CCAM (Mark3)
- Mean humidity tends to decrease all year except around March at each site in CCAM (Mark2), while increases are more prevalent in CCAM (Mark 3) in Hobart, Melbourne and Sydney

The mean results represent changes spread across all ten deciles, while the extreme changes represent changes in decile ten (very high) for temperature and wind-speed, and decile 1 (very low) for relative humidity. The mean and extreme changes can be significantly different for some cases. For example, the spring-summer increases in extremely high temperature are larger than the increases in mean temperature. Similarly, the decreases in extremely low humidity are larger than the decreases in mean humidity.

2.4 Apply the climate change scenarios to observed weather data

Changes in each monthly decile were applied to the observed daily weather data, thus creating "new" 30-year weather data centred on 2020 (low and high global warming) and 2050 (low and high global warming). For example, if the maximum temperature on 19 January 2003 was 27.5^oC, and this was in decile 7 of January observed maximum temperatures, and the CCAM (Mark2) decile 7 high scenario for January in 2050 was a warming of 2.3^oC, then the "new" temperature for a simulated 19 January would be 29.8^oC. The "new" weather data were then used in calculations of SDI, KBDI, FFDI and GFDI for 2020 and 2050.

3. Results

McArthur Mark 5 Forest Fire Danger Index (FFDI; Noble *et al*,, 1980) is defined as:

$$FFDI = 2\exp(0.987\log D - 0.45 + 0.0338T + 0.0234V - 0.0345H)$$

where: H = relative humidity from 0-100%
T = air temperature in degrees Celsius
V = average wind-speed 10 metres above the ground, in metres per second
D = drought factor in the range 0-10

The drought factor, D, can be defined in different ways, e.g. the Keetch Byram Drought Index (KBDI; Keetch and Byram, 1968) and the Mount Soil Dryness Index (SDI; Mount, 1972), The KBDI is a function of days since last rain, assuming a 200 mm soil moisture capacity. Mount (1972) modified the KBDI on the basis of Tasmanian experience and developed the SDI (Beer *et al*,, 1988). In the present study, we have used the Griffiths (1999) drought factor because this is standard practice in the Bureau of Meteorology. It uses the KBDI and includes the effect of evapotranspiration. The difference between SDI and KBDI lies in the way evapotranspiration is handled. KBDI uses an exponential relationship, while SDI uses a linear regression. Both have their shortcomings, but SDI is probably most applicable to Tasmania, where it was developed, and least applicable in inland NSW. SDI is almost always higher than KBDI, and results in slightly higher FFDI values. Although we use Griffiths drought factor, results are presented in the appendices for SDI and KBDI since these were required by the sponsors of this study.

The McArthur Mark 4 Grassland Fire Danger Index (GFDI; Purton, 1982) is defined as:

$$GFDI=10^{x}$$

where $x = (-0.6615+1.027\log10(Q)-0.004096(100-C)^{1.536}+0.01201T+0.2789\sqrt{V}-0.9577\sqrt{RH})$

and Q is fuel quantity (t/ha)...[we assume a standard 4.5 t/ha]
C is curing factor (0-100%) [we assume 100% fully cured]
T is temperature (Celsius)
V is wind speed (km/hr)
RH is relative humidity (%)

The degree of grassland curing refers to the proportion of cured and/or dead material in a grassland fuel complex, and has a significant effect on fire behaviour, in particular potential fire spread (Anderson and Pearce, 2003). The GFDI results are sensitive to the curing factor, as shown in Figure 6. Our assumption of 100% curing represents a worst-case scenario. An assumption of 80% curing could reduce the GFDI results by about 60%. In the absence of a pasture growth model, the choice of curing factor is arbitrary. It is likely that the 100% assumption overestimates GFDI in winter/spring and has greater accuracy in summer/autumn. A change in climate could lead to earlier and /or more efficient curing, or to a change in vegetation type which has different curing properties. Hence, the GFDI results should be treated with caution.

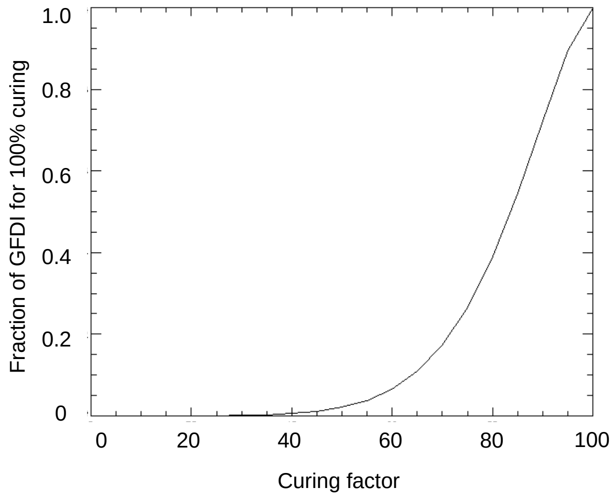


Figure 6: Relationship between GFDI and curing factor.

3.1 Drought factors: SDI and KBDI

Appendices 1 and 2 show frequency distributions of SDI and KBDI at each of the 17 sites, for present, 2020 and 2050 conditions. In future, there is a strong tendency toward higher values. In some cases, the frequency of reaching 150-200 (very dry) doubles by 2050 in the high scenarios.

3.2 Forest fire danger index

The FFDI results were calculated in three ways.

- Annual-average cumulative FFDI, denoted ΣFFDI
- Monthly-average FFDI
- Daily-average FFDI.

Table 1 shows the "present" average ΣFFDI at each site. Inland areas have values around 3000-5000, while southern and coastal areas have values around 1700-2600. Site selection was constrained by availability of high quality data, so the sites used are not always representative of large areas. For example, Melbourne ΣFFDI values are less than those at nearby Laverton because the former are based on data from a highly urbanised area with lower wind-speeds and higher rainfall. Hence Melbourne values are more representative of inner suburbs while Laverton values are more representative of outer Melbourne suburbs. Sydney values are less than those at nearby Williamtown because the former are based on data measured near Botany Bay with higher humidity. Richmond values are representative of outer Sydney suburbs and the Blue Mountains.

All sites, except Hobart, show an increase in annual ΣFFDI in both 2020 and 2050. For CCAM (Mark2), the increases are generally 2-10% by 2020 and 5-25% by 2050. For CCAM (Mark3), the increases are slightly greater: generally 3-10% by 2020 and 8-30% by 2050. Hobart shows negligible change since small increases in temperature are offset by increases in humidity. However, ΣFFDI is a fairly conservative measure of fire risk because it hides information about monthly and daily extremes. Therefore, monthly and daily FFDI values were examined.

Table 1: Annual-average ∑FFDI at 17 sites for present (1974-2003) conditions, and percentage changes for 2020 and 2050, for low and high rates of global warming, in CCAM (Mark2) and CCAM (Mark3).

Site	Present	CCAM (Mark2)				CCAM (Mark3)			
		2020 low %	2020 high %	2050 low %	2050 high %	2020 low %	2020 high %	2050 low %	2050 high %
Canberra	2913	4	8	10	26	4	10	11	29
Bourke	5869	4	9	9	25	3	7	7	19
Cabramurra	501	5	10	10	26	7	14	15	40
Cobar	5818	4	10	10	26	3	8	8	22
Coffs Harbour	2002	2	5	5	12	3	6	6	15
Nowra	2507	1	4	4	13	2	6	6	18
Richmond	3049	4	8	8	20	4	8	8	21
Sydney	2158	2	4	5	12	3	7	7	19
Wagga	4047	4	8	9	23	4	9	9	25
Williamtown	2641	2	5	5	13	3	7	7	18
Bendigo	2854	3	8	8	22	3	8	8	23
Laverton	2456	3	8	8	21	4	9	9	24
Melbourne	2121	3	8	8	21	3	8	8	22
Mildura	5898	3	7	7	17	3	8	8	21
Sale	2207	3	8	8	21	4	8	8	23
Hobart	1723	0	0	0	-1	0	1	1	2
Launceston	1677	1	3	3	8	3	6	6	17

Appendix 3 shows monthly-average FFDI and daily-average frequency distributions of FFDI at each site. Most sites currently have highest fire danger in spring and summer (blue curves). The spring peak is distinctive for coastal NSW sites, whereas the summer peak is typical of southern and inland sites (c.f. Figure 1). In 2020 and 2050, the curves move upward, indicating higher fire danger, particularly in spring, summer and autumn. At NSW coastal stations, the largest increases occur in spring. Periods suitable for prescribed (control) burning are likely to move toward winter.

The daily-average frequency distributions of FFDI have five intensity categories: low (less than 5), moderate (5-12), high (13-25), very high (25-49) and extreme (at least 50). At all sites, except Hobart, Launceston and Cabramurra, there is an increase in the frequency of very high and extreme days by 2020 and 2050. These are the two categories of most interest to fire management agencies. By 2020, the combined frequencies of very high and extreme FFDI (Table 2) generally rise 4-20% for CCAM (Mark2) and 6-25% for CCAM (Mark3). By 2050, the increases are generally 15-55% for CCAM (Mark2) and 20-70% for CCAM (Mark3).

Changes in the frequencies of extreme FFDI days (Table 3) are largest inland, e.g. at Bourke, Cobar, Mildura and Wagga. By 2020, the increases are generally 10-30% for CCAM (Mark2) and 15-40% for CCAM (Mark3). By 2050, the increases are generally 20-80% for CCAM (Mark2) and 40-120% for CCAM (Mark3). At many sites, there is a doubling (or greater) of the number of extreme days by 2050 for the high scenario. Tasmania is relatively unaffected. In Hobart, the rise in temperature is offset by a rise in humidity.

Table 2: Average number of days when the FFDI rating is "very high" or "extreme" under present conditions (1974-2003). Results are also shown for the years 2020 and 2050, for two climate models (CCAM Mark2 and CCAM Mark3), and two rates of global warming (low and high).

Site	Present	CCAM (Mark2)				CCAM (Mark3)			
		2020 low	2020 high	2050 low	2050 high	2020 low	2020 high	2050 low	2050 high
Canberra	23.1	25.6	27.5	27.9	36.0	26.0	28.6	28.9	38.3
Bourke	69.5	75.2	83.3	84.0	106.5	73.9	80.3	80.6	96.2
Cabramurra	0.3	0.3	0.4	0.4	0.7	0.4	0.4	0.5	1.0
Cobar	81.8	87.9	96.2	96.6	118.3	86.6	92.8	93.0	108.6
Coffs Harbour	4.4	4.7	5.1	5.1	6.3	4.7	5.6	5.6	7.6
Nowra	13.4	13.9	14.7	14.8	17.5	14.2	15.6	15.6	19.9
Richmond	11.5	12.9	14.0	14.1	17.5	13.1	14.3	14.4	19.1
Sydney	8.7	9.2	9.8	9.8	11.8	9.5	11.1	11.3	15.2
Wagga	49.6	52.7	57.3	57.6	71.5	52.8	57.4	57.7	71.9
Williamtown	16.4	17.2	18.2	18.4	20.9	17.3	19.4	19.4	23.6
Bendigo	17.8	19.5	21.3	21.4	27.3	19.7	21.9	22.0	29.8
Laverton	15.5	16.4	17.3	17.3	21.2	16.6	17.8	17.8	22.3
Melbourne	9.0	9.8	10.7	10.8	13.9	9.8	11.1	11.2	14.7
Mildura	79.5	83.9	89.5	89.9	104.8	84.6	90.7	90.9	107.3
Sale	8.7	9.3	10.0	10.1	12.1	9.6	10.7	10.8	14.0
Hobart	3.4	3.4	3.4	3.4	3.4	3.4	3.5	3.5	3.5
Launceston	1.5	1.5	1.5	1.6	2.0	1.6	1.9	1.9	3.1

Table 3: Average number of days when the FFDI rating is "extreme" under present conditions (1974-2003). Results are also shown for the years 2020 and 2050, for two climate models (CCAM Mark2 and CCAM Mark3), and two rates of global warming (low and high).

Site	Present	CCAM (Mark2)				CCAM (Mark3)			
		2020 low	2020 high	2050 low	2050 high	2020 low	2020 high	2050 low	2050 high
Canberra	2.2	2.6	3.0	3.0	4.7	2.5	3.5	3.5	5.7
Bourke	6.4	7.6	8.8	8.9	14.4	7.5	8.8	8.9	14.2
Cabramurra	0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.1
Cobar	8.5	9.8	12.2	12.4	20.5	9.7	12.2	12.3	19.9
Coffs Harbour	0.5	0.6	0.6	0.6	0.7	0.6	0.7	0.7	0.9
Nowra	2.5	2.7	3.1	3.1	3.5	3.1	3.4	3.4	5.3
Richmond	1.5	1.7	1.9	1.9	2.4	1.8	2.0	2.0	3.2
Sydney	1	1.0	1.1	1.1	1.4	1.2	1.4	1.4	2.5
Wagga	6.3	7.0	8.0	8.2	13.2	6.9	8.3	8.4	14.5
Williamtown	2.8	3.1	3.3	3.3	4.2	3.3	3.7	3.7	5.5
Bendigo	1.6	1.9	2.2	2.2	3.2	2.0	2.3	2.3	3.9
Laverton	3.4	3.6	4.1	4.1	5.0	3.7	4.4	4.5	6.0
Melbourne	0.6	0.7	0.8	0.8	1.5	0.7	0.9	0.9	1.9
Mildura	10.4	11.2	12.7	12.8	16.9	11.7	13.5	13.6	20.1
Sale	1.1	1.2	1.5	1.5	2.1	1.3	1.7	1.7	2.6
Hobart	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3
Launceston	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

3.3 Grassland fire danger index

Appendix 4 shows monthly-average GFDI and daily-average frequency distributions of GFDI at each site. The GFDI has five intensity categories: low (less than 2.5), moderate (2.5-7.5), high (7.5-20), very high (20-50) and extreme (50-200) (Cheney, 1997). Most sites currently have highest fire danger in spring and summer. The magnitude of the GFDI is always higher than the FFDI since the GFDI is more strongly influenced by wind-speed and we have assumed a worst-case scenario of 100% curing. In 2020 and 2050, the GFDI curves move upward, indicating higher grassfire danger, particularly in spring, summer and autumn. There is an increase in the frequency of very high and extreme days by 2020 and 2050 (Table 4). By 2020, the increases are generally 0-15% for CCAM (Mark2) and 5-20% for CCAM (Mark3). By 2050, the increases are generally 5-30% for CCAM (Mark2) and 15-40% for CCAM (Mark3).

Changes in extreme days are generally largest inland, e.g. at Bourke, Cobar, Mildura and Wagga (Table 5). By 2020, the increases are generally 5-20% for CCAM (Mark2) and 10-30% for CCAM (Mark3). By 2050, the increases are generally 10-30% for CCAM (Mark2) and 30-80% for CCAM (Mark3). At many sites, there is a doubling (or greater) of the number of days classified as extreme by 2050 for the high scenario.

Table 4: Average number of days when the GFDI rating is "very high" or "extreme" under present conditions (1974-2003). Results are also shown for the years 2020 and 2050, for two climate models (CCAM Mark2 and CCAM Mark3), and two rates of global warming (low and high).

Site	Present	CCAM (Mark2)				CCAM (Mark3)			
		2020 low	2020 high	2050 low	2050 high	2020 low	2020 high	2050 low	2050 high
Canberra	96.8	100.3	103.7	104.0	113.1	103.5	110.3	110.6	129.0
Bourke	90.6	97.5	102.9	103.3	117.9	97.7	102.7	103.0	117.0
Cabramurra	11.6	11.6	11.8	11.8	12.6	12.5	13.8	13.9	18.6
Cobar	112.8	124.1	129.0	129.4	146.6	124.0	129.5	130.1	148.1
Coffs Harbour	86.4	99.9	101.8	101.8	109.1	101.5	105.2	105.6	117.7
Nowra	71.7	80.3	81.7	81.8	86.3	83.5	88.5	88.9	104.0
Richmond	40.4	44.1	44.8	44.8	47.1	45.3	47.4	47.5	55.1
Sydney	116.2	117.6	120.0	120.1	126.8	122.1	129.3	129.7	153.5
Wagga	104.6	110.7	114.4	114.4	123.5	112.5	118.7	119.0	134.2
Williamtown	123.1	132.2	134.9	135.1	144.1	135.0	141.8	142.5	162.9
Bendigo	61.1	63.6	65.8	65.9	72.4	65.0	69.5	69.7	81.7
Laverton	110.1	109.4	111.7	111.9	118.6	111.8	117.4	117.9	131.7
Melbourne	38.7	41.2	41.2	42.2	45.7	42.3	45.0	45.2	54.5
Mildura	146.7	149.1	153.6	153.9	165.6	150.6	157.6	157.0	174.6
Sale	95.4	102.5	104.0	104.1	109.3	104.9	110.2	110.3	124.2
Hobart	67.5	67.5	67.2	67.2	66.1	68.1	68.8	69.0	71.5
Launceston	73.3	73.4	72.3	72.3	69.4	78.5	85.0	85.5	102.8

Table 5: Average number of days when the GFDI rating is "extreme" under present conditions (1974-2003). Results are also shown for the years 2020 and 2050, for two climate models (CCAM Mark2 and CCAM Mark3), and two rates of global warming (low and high).

Site	Present	CCAM (Mark2)				CCAM (Mark3)			
		2020 low	2020 high	2050 low	2050 high	2020 low	2020 high	2050 low	2050 high
Canberra	18.8	19.3	20.2	20.3	23.7	20.8	23.6	23.9	32.8
Bourke	17.2	19.4	21.9	22.2	29.0	19.6	22.6	22.8	30.6
Cabramurra	0.8	0.8	0.8	0.8	0.9	0.8	1.0	1.0	1.8
Cobar	21.8	26.2	28.6	28.7	36.7	26.8	29.8	30.0	40.6
Coffs Harbour	7.8	10.6	10.9	10.9	11.9	11.1	12.8	12.8	17.8
Nowra	18.3	20.9	21.1	21.1	21.8	21.8	23.5	23.6	29.8
Richmond	7.5	8.7	8.8	8.9	9.6	9.2	10.0	10.0	13.5
Sydney	19.8	20.0	20.4	20.4	21.5	21.6	24.9	25.3	34.4
Wagga	25	27.7	29.8	30.0	36.4	28.5	31.4	31.6	42.7
Williamtown	27.9	30.4	30.7	30.8	32.4	31.5	34.6	34.7	43.6
Bendigo	9.5	9.9	10.4	10.4	11.9	10.4	11.8	11.9	16.3
Laverton	29.6	29.6	30.2	30.2	31.6	30.5	32.2	32.4	38.9
Melbourne	5.8	6.3	6.4	6.4	7.8	6.6	7.6	7.6	10.2
Mildura	30.1	31.0	32.9	33.0	39.0	32.4	36.1	36.4	48.3
Sale	17.3	19.2	19.8	19.8	21.2	20.7	23.4	23.6	30.9
Hobart	9.1	9.0	8.9	8.9	8.7	9.3	9.4	9.4	10.0
Launceston	4.6	4.6	4.3	4.3	3.7	5.3	6.0	6.1	9.6

3.4 Synthesis of results for each site

This section summarises FFDI and GFDI results for each site, based on climate change simulations from two climate models (CCAM Mark2 and CCAM Mark3). Results from other models may be slightly different, but quantification of that uncertainty is beyond the scope of this report. The word "could " is used below to emphasize that the projections are not predictions. The monthly-average FFDI threshold selected for each site is arbitrary, and is not intended to define a fire season. It simply provides a reference period between spring and autumn against which changes in the duration of fire-weather risk can be compared.

Canberra

The average annual accumulated FFDI is currently 2913. This could increase 4-10% by 2020 and 10-29% by 2050. The monthly-average FFDI currently exceeds 10 from mid-November to mid-March. This could extend from early November to mid-March by 2020, and from mid-October to early April by 2050. On average, there are currently 23.1 days when the FFDI rating is very high or extreme. This could increase to 25.6-28.6 days by 2020 and 27.9-38.3 days by 2050. There are currently 96.8 days when the GFDI rating is very high or extreme. This could increase to 100.3-110.3 days by 2020 and 104.0-129.0 days by 2050.

Bourke

The average annual accumulated FFDI is currently 5869. This could increase 4-9% by 2020 and 9-25% by 2050. The monthly-average FFDI currently exceeds 20 from late October to late February. This could extend from early October to mid-March by 2020, and from early September to late March by 2050. On average, there are currently 69.5 days when the FFDI rating is very high or extreme. This could increase to 73.9-83.3 days by 2020 and 80.6-106.5 days by 2050. There are currently 90.6 days when the GFDI rating is very high or extreme. This could increase to 97.5-102.9 days by 2020 and 103.0-117.9 days by 2050.

Cabramurra

The average annual accumulated FFDI is currently 501. This could increase 5-14% by 2020 and 10-40% by 2050. The monthly-average FFDI currently exceeds 2 from early December to mid-March. This could extend from mid November to mid-March by 2020, and from mid-October to early April by 2050. On average, there are currently 0.3 days when the FFDI rating is very high or extreme. This could increase to 0.3-0.4 days by 2020 and 0.4-1.0 days by 2050. There are currently 11.6 days when the GFDI rating is very high or extreme. This could increase to 11.6-13.8 days by 2020 and 11.8-18.6 days by 2050.

Cobar

The average annual accumulated FFDI is currently 5818. This could increase 4-10% by 2020 and 10-26% by 2050. The monthly-average FFDI currently exceeds 20 from early November to mid-March. This could extend from mid-October to mid-March by 2020, and from mid-September to late March by 2050. On average, there are currently 81.8 days when the FFDI rating is very high or extreme. This could increase to 86.6-96.2 days by 2020 and 93.0-118.3 days by 2050. There are currently 112.8 days when the GFDI rating is very high or extreme. This could increase to 124.0-129.5 days by 2020 and 129.4-148.1 days by 2050.

Coffs Harbour

The average annual accumulated FFDI is currently 2002. This could increase 2-6% by 2020 and 5-15% by 2050. The monthly-average FFDI currently exceeds 8 from mid-August to mid-October. This could extend one week earlier (CCAM Mark2) or two weeks later (CCAM Mark3) by 2020, and two weeks earlier (CCAM Mark2) or three weeks later (CCAM Mark3) by 2050. On average, there are currently 4.4 days when the FFDI is very high or extreme. This could increase to 4.7-5.6 days by 2020 and 5.1-7.6 days by 2050. There are currently 86.4 days when the GFDI rating is very high or extreme. This could increase to 99.9-105.2 days by 2020 and 101.8-117.7 days by 2050.

Nowra

The average annual accumulated FFDI is currently 2507. This could increase 1-6% by 2020 and 4-18% by 2050. The monthly-average FFDI currently exceeds 8 from early September to mid-January. This could extend from late August to mid-January by 2020, and from early August to early February by 2050. On average, there are currently 13.4 days when the FFDI rating is very high or extreme. This could increase to 13.9-15.6 days by 2020 and 14.8-19.9 days by 2050. There are currently 71.7 days when the GFDI rating is very high or extreme. This could increase to 80.3-88.5 days by 2020 and 81.8-104.0 days by 2050.

Richmond

The average annual accumulated FFDI is currently 3049. This could increase 4-8% by 2020 and 8-21% by 2050. The monthly-average FFDI currently exceeds 10 from early September to mid-January. This could extend from mid-August to late January by 2020, and from early August to early February by 2050. On average, there are currently 11.5 days when the FFDI rating is very high or extreme. This could increase to 12.9-14.3 days by 2020 and 14.1-19.1 days by 2050. There are currently 40.4 days when the GFDI rating is very high or extreme. This could increase to 44.1-47.4 days by 2020 and 44.8-55.1 days by 2050.

Sydney

The average annual accumulated FFDI is currently 2158. This could increase 2-7% by 2020 and 5-19% by 2050. The monthly-average FFDI currently exceeds 6 from early August to late December. This could extend from early August to mid-January by 2020, and from late July to mid-February by 2050. On average, there are currently 8.7 days when the FFDI rating is very high or extreme. This could increase to 9.2-11.1 days by 2020 and 9.8-15.2 days by 2050. There are currently 116.2 days when the GFDI rating is very high or extreme. This could increase to 117.6-129.3 days by 2020 and 120.1-153.5 days by 2050.

Wagga

The average annual accumulated FFDI is currently 4047. This could increase 4-9% by 2020 and 9-25% by 2050. The monthly-average FFDI currently exceeds 20 from early December to late February. This could extend from late November to early March by 2020, and from mid-November to early March by 2050. On average, there are currently 49.6 days when the FFDI rating is very high or extreme. This could increase to 52.7-57.4 days by 2020 and 57.6-71.9 days by 2050. There are currently 104.6 days when the GFDI rating is very high or extreme. This could increase to 110.7-118.7 days by 2020 and 114.4-134.2 days by 2050.

Williamtown

The average annual accumulated FFDI is currently 2641. This could increase 2-7% by 2020 and 5-18% by 2050. The monthly-average FFDI currently exceeds 8 from late August to late January. This could extend from mid-August to late January by 2020, and from early August to early February to early April by 2050. On average, there are currently 16.4 days when the FFDI rating is very high or extreme. This could increase to 17.2-19.4 days by 2020 and 18.4-23.6 days by 2050. There are currently 123.1 days when the GFDI rating is very high or extreme. This could increase to 132.2-141.8 days by 2020 and 135.1-162.9 days by 2050.

Bendigo

The average annual accumulated FFDI is currently 2854. This could increase 3-8% by 2020 and 8-23% by 2050. The monthly-average FFDI currently exceeds 10 from late November to late March. This could extend from early November to late March by 2020, and from late October to early April by 2050. On average, there are currently 17.8 days when the FFDI rating is very high or extreme. This could increase to 19.5-21.9 days by 2020 and 21.4-29.8 days by 2050. There are currently 61.1 days when the GFDI rating is very high or extreme. This could increase to 63.6-69.5 days by 2020 and 65.9-81.7 days by 2050.

Laverton

The average annual accumulated FFDI is currently 2913. This could increase 3-9% by 2020 and 8-24% by 2050. The monthly-average FFDI currently exceeds 10 from mid-December to early March. This could extend from early December to mid-March by 2020, and from early November to late March by 2050. On average, there are currently 15.5 days when the FFDI rating is very high or extreme. This could increase to 16.4-17.8 days by 2020 and 17.3-22.3 days by 2050. There are currently 110.1 days when the GFDI rating is very high or extreme. This could increase to 109.4-117.4 days by 2020 and 111.9-131.7 days by 2050.

Melbourne

The average annual accumulated FFDI is currently 2121. This could increase 3-8% by 2020 and 8-22% by 2050. The monthly-average FFDI currently exceeds 8 from mid-December to mid-March. This could extend from early December to late March by 2020, and from early November to late April by 2050. On average, there are currently 9.0 days when the FFDI rating is very high or extreme. This could increase to 9.8-11.1 days by 2020 and 10.8-14.7 days by 2050. There are currently 38.7 days when the GFDI rating is very high or extreme. This could increase to 41.2-45.0 days by 2020 and 42.2-54.5 days by 2050.

Mildura

The average annual accumulated FFDI is currently 5898. This could increase 3-8% by 2020 and 7-21% by 2050. The monthly-average FFDI currently exceeds 20 from late October to mid-March. This could extend from mid-October to mid-March by 2020, and from early-October to late March by 2050. On average, there are currently 79.5 days when the FFDI rating is very high or extreme. This could increase to 83.9-90.7 days by 2020 and 89.9-107.3 days by 2050. There are currently 146.7 days when the GFDI rating is very high or extreme. This could increase to 149.1-157.6 days by 2020 and 153.9-174.6 days by 2050.

Sale

The average annual accumulated FFDI is currently 2207. This could increase 3-8% by 2020 and 8-23% by 2050. The monthly-average FFDI currently exceeds 8 from early December to mid-March. This could extend from late November to mid-March by 2020, and from late October to late March by 2050. On average, there are currently 8.7 days when the FFDI rating is very high or extreme. This could increase to 9.3-10.7 days by 2020 and 10.1-14.0 days by 2050. There are currently 95.4 days when the GFDI rating is very high or extreme. This could increase to 102.5-110.2 days by 2020 and 104.1-124.2 days by 2050.

Hobart

The average annual accumulated FFDI is currently 1723. This is unlikely to change by more than 1 or 2% over the next 50 years since projected increases in temperature are offset by increases in rainfall and humidity. The monthly-average FFDI currently exceeds 6 from early December to mid-March and shows little change by 2050. On average, there are currently 3.4 days when the FFDI rating is very high or extreme. This is unlikely to change over the next 50 years. There are currently 67.5 days when the GFDI rating is very high or extreme. This could increase to 67.5-68.8 days by 2020 and 67.2-71.5 days by 2050.

Launceston

The average annual accumulated FFDI is currently 1677. This could increase 1-6% by 2020 and 3-17% by 2050. The monthly-average FFDI currently exceeds 10 from late November to late March. This could extend from mid-November to late March by 2020, and from early November to early April by 2050. On average, there are currently 1.5 days when the FFDI rating is very high or extreme. This could increase to 1.5-1.9 days by 2020 and 1.6-3.1 days by 2050. There are currently 73.3 days when the GFDI rating is very high or extreme. This could increase to 73.4-85.0 days by 2020 and 72.3-102.8 days by 2050.

4. Discussion

Following the widespread fires in December 2002 and January 2003, a number of inquiries were undertaken. For the ACT, the McLeod Inquiry Report (2003) recommended a range of fire mitigation activities to be undertaken prior to, and during, the 2003-04 bushfire season, with an additional $1.684 million being sought for that purpose, adding to the $0.5 million provided in the 2003-04 budget.

The COAG (2004) *Report of the National Inquiry on Bushfire Mitigation and Management* stated "Climate change is likely to increase the frequency, intensity and size of bushfires in much of Australia in the future". It is possible that changes in the FFDI and other indices will require prescribed burning to take place a little earlier in spring and a little later in autumn, prolonging the effective fire season, increasing the personal and employer cost for volunteers, and increasing the cost of fire fighters. Climate change impacts would be seen in potentially prolonged fire danger periods, increased numbers of total fire ban days, increased community based educational and organizational programs such as Community Fire Guard (2005), and in increased reliance on the good will of employers or volunteers. The summary concluded that "more research is needed on building design and materials, climate and climate change, fire behaviour and ecological responses, individual and community psychology and social processes, and Indigenous Australians' knowledge and use of fire". It also concluded that "long-term strategic research, planning and investment are necessary if the Australian Government and state and territory governments are to prepare for the changes to bushfire regimes and events that will be caused by climate change".

The *Report of the Inquiry into the 2002–2003 Victorian Bushfires* (Esplin *et al,* 2003) noted that "The weather leading up to a fire season is not the only aspect of climate that influences the severity of a fire event. The weather at the time of a fire has a major impact on fire behaviour and on the ease of suppression. In relation to the 2002–03 fire season, the Bureau of Meteorology stated: The very dry conditions leading into the 2002/03 fire season do not in themselves fully explain the intensity and longevity of the fire episodes. A significant contributor to the long period for which the 2003 bushfires remained active was the absence of any significant rain for several weeks after". It also stated "A prolonged and severe drought, especially throughout much of the southern half of Australia, is the stand-out climatic feature of the 2002–03 fire season. Fire agencies need to be responsive to macro indicators of this kind, using them to assist with annual planning and preparation activities, as well as to match their response capacity to daily weather conditions. Operational responses during drought periods should reflect the 'worst case' scenario and include optimum available resourcing. Although the full extent of the fire threat may not be realised, operational planning must take account of this possibility".

The results of this study provide scenarios that reconfirm the findings of these inquiries. The impacts of climate change are likely to pose a number of challenges for natural and human systems. However, few impact assessments have been done. It is likely that an increase in the frequency and intensity of fire-weather would:

- alter the distribution and composition of ecosystems (Cary, 2002)
- lower the yield and quality of water from fire-affected catchments (Lavoral and Steffen, 2004)
- threaten the security of plantation forests
- increase smoke-related respiratory illness
- increase emissions of greenhouse gases to the atmosphere
- increase damage to property, livestock and crops
- increase the exposure of insurance companies to loss (Coleman *et al*,, 2004)
- increase the risk of injury, trauma and death to humans (BTE, 2001).

5. Gaps in knowledge and research priorities

This study has quantified present average fire-weather risk at 17 sites in southeast Australia and potential changes for the years 2020 and 2050. A number of knowledge gaps remain:

- Quality of daily wind data at most sites in Australia
- Quality of daily humidity data at sites outside southeast Australia
- The effect of scenarios based on other climate models
- Future changes in intervals between rainfall events during the fire season
- Future changes in ignition (natural and anthropogenic)
- Future changes in fuel load, allowing for carbon dioxide fertilization of vegetation.
- Potential impacts on biodiversity, water yield and quality from fire affected catchments, forestry, greenhouse gas emissions, emergency management and insurance.

Priorities for further research are outlined in Figure 7, including:

- Testing and rehabilitation of observed humidity and wind data (underway within the Bureau of Meteorology, supported by the Bushfire CRC).
- Deriving better regional and local predictions of fire weather (especially extreme events). This could involve creation of climate change scenarios from other models (monthly output from a new suite of 23 models was made available by the IPCC in mid-2005), and finer resolution daily data using "downscaling" methods.
- Extending the analysis to other regions, e.g. Queensland, South Australia, Western Australia and the Northern Territory.
- Modelling of changed vegetation growth and fuel dynamics under climate change. This requires incorporation of the effects of changed atmospheric composition and climate into interactive models of the Australian biosphere.
- Modelling that integrates changing climate and fuels with landscape features to predict the nature and extent of fire under a range of fire management scenarios, including prescribed burning and suppression.
- Hydrological and ecological modelling to assess impacts on water and biodiversity.
- Assessment of potential impacts on community safety and insurance liabilities.
- Using satellite remote sensing (Sentinel fire mapping based on MODIS, NCAS land cover change based on Landsat, and other data) to monitor the extent and nature of fire, recovery of vegetation after fire, and greenhouse gas emissions from fire.

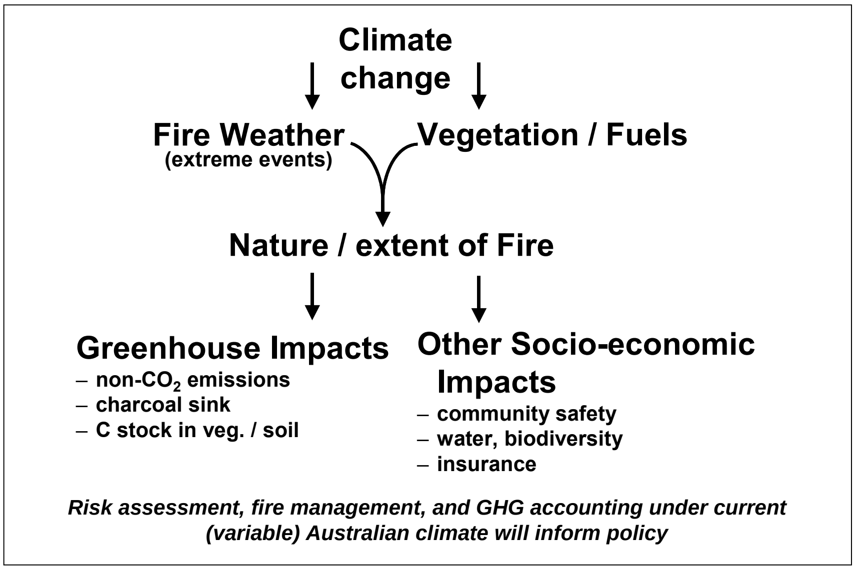


Figure 7. Proposed agenda for research to address knowledge gaps and inform policy.

Broader participation in this research is required in order to engage relevant groups in government, industry and the community. Outcomes of discussions might include identification of:

- Regional fire management issues affected by climate variability and climate change in each State/Territory
- Other information available for assessing current fire vulnerability and potential changes due to greenhouse warming
- Important biophysical and behavioural/management thresholds
- Technical adaptation options
- Institutional processes that influence adaptation
- Information required for future planning (e.g. potential change in seasonal average fire risk, frequency of extreme fire-risk days, interval between fires, fire intensity, fuel load, etc.)
- Information about fire damage from insurance companies and government sources in each State/Territory.

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Appendix 1 IPCC scenarios of global warming

The IPCC (2001) attributes most of the global warming observed over the last 50 years to greenhouse gases released by human activities. To estimate future climate change, the IPCC (SRES, 2000) prepared forty greenhouse gas and sulfate aerosol emission scenarios for the 21st century that combine a variety of assumptions about demographic, economic and technological driving forces likely to influence such emissions in the future. They do not include the effects of measures to reduce greenhouse gas emissions, such as the Kyoto Protocol.

Each scenario represents a variation within one of four 'storylines': A1, A2, B1 and B2. The experts who created the storylines (described below) were unable to arrive at a most likely scenario, and probabilities were not assigned to the storylines.

A1 describes a world of very rapid economic growth in which the population peaks around 2050 and declines thereafter and there is rapid introduction of new and more efficient technologies. The three sub-groups of A1 are fossil fuel intensive (A1FI), non-fossil fuel using (A1T), and balanced across all energy sources (A1B).

The A2 storyline depicts a world of regional self-reliance and preservation of local culture. In A2, fertility patterns across regions converge slowly, leading to a steadily increasing population and per capita economic growth and technological change is slower and more fragmented than for the other storylines.

The B1 storyline describes a convergent world with the same population as in A1, but with an emphasis on global solutions to economic, social and environmental sustainability, including the introduction of clean, efficient technologies.

The B2 storyline places emphasis on local solutions to economic, social and environmental sustainability. The population increases more slowly than that in A2. Compared with A1 and B1, economic development is intermediate and less rapid, and technological change is more diverse.

The projected carbon dioxide and sulfate aerosol emissions, and carbon dioxide concentrations, are shown in Figure 1-A1 (a, b, c). Emissions of other gases and other aerosols were included in the scenarios but are not shown in the figure. By incorporating these scenarios into computer models of the climate system, the IPCC (2001) estimated a global-average warming of 0.7 to 2.5^{o}C by the year 2050 and 1.4 to 5.8^{o}C by the year 2100 (Figure 2-A1d). The analysis allowed for both uncertainty in projecting future greenhouse gas and aerosol concentrations (behavioural uncertainty) and uncertainty due to differences between models in their response to atmospheric changes (scientific uncertainty). Projected sea-level rise is shown in Figure 2-A1e.

The range of uncertainty in projections of global warming increases with time. Half of this range is due to uncertainty about human socio-economic behaviour, and consequent emissions of greenhouse gases and sulfate aerosols. The other half of the range is due to different climate model responses to these scenarios of greenhouse gases and sulfate aerosols. Each of the models is considered equally reliable.

Climate simulations indicate that warming will be greater near the poles and over the land, and that global-average rainfall will increase. More rainfall is likely nearer the poles and in the tropics, and less rainfall is expected in the middle latitudes such as southern Australia.

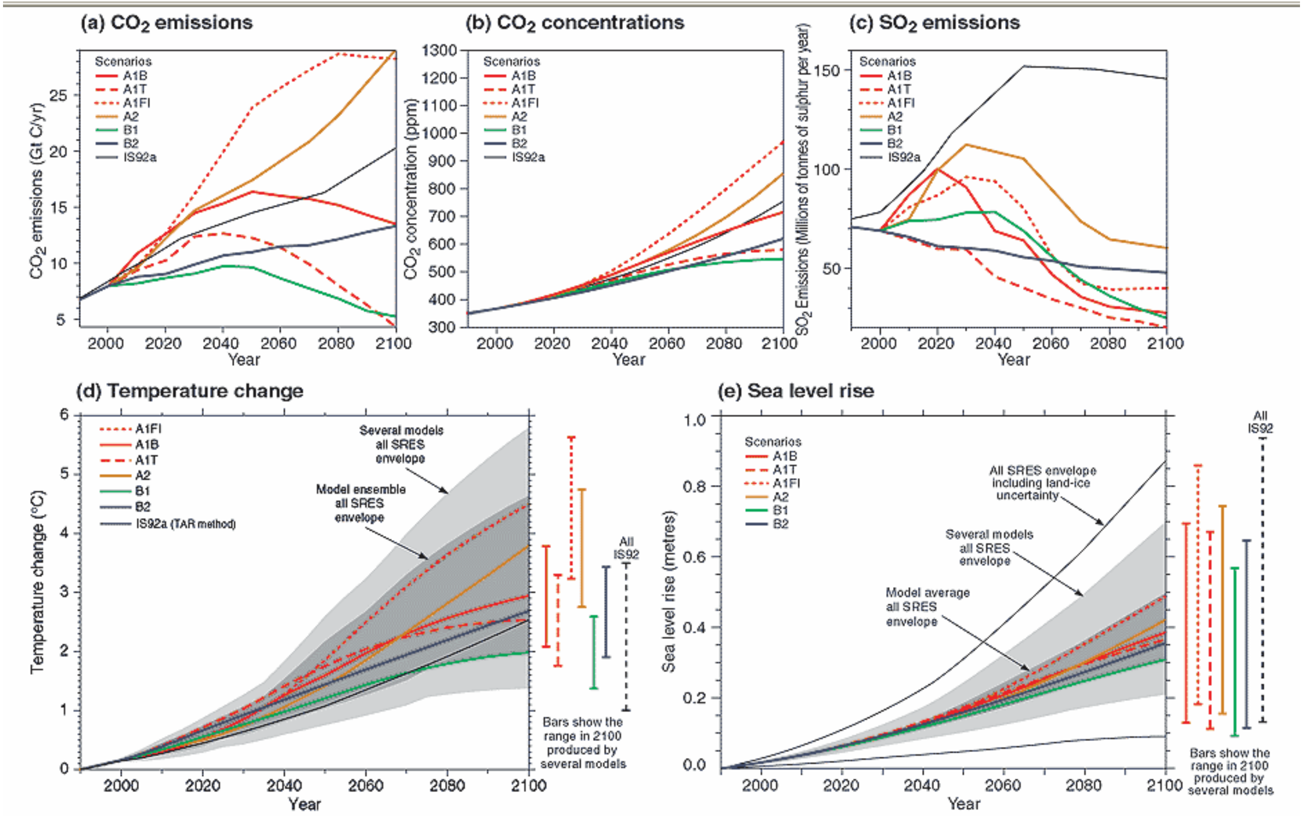


Figure 1-A1: (a) carbon dioxide (CO_2) emissions for the six illustrative SRES (2000) scenarios, and the superseded IS92a scenario, (b) CO_2 concentrations, (c) anthropogenic sulphur dioxide (SO_2) emissions, (d) and (e) show the projected temperature and sea level responses, respectively. Source: IPCC (2001).

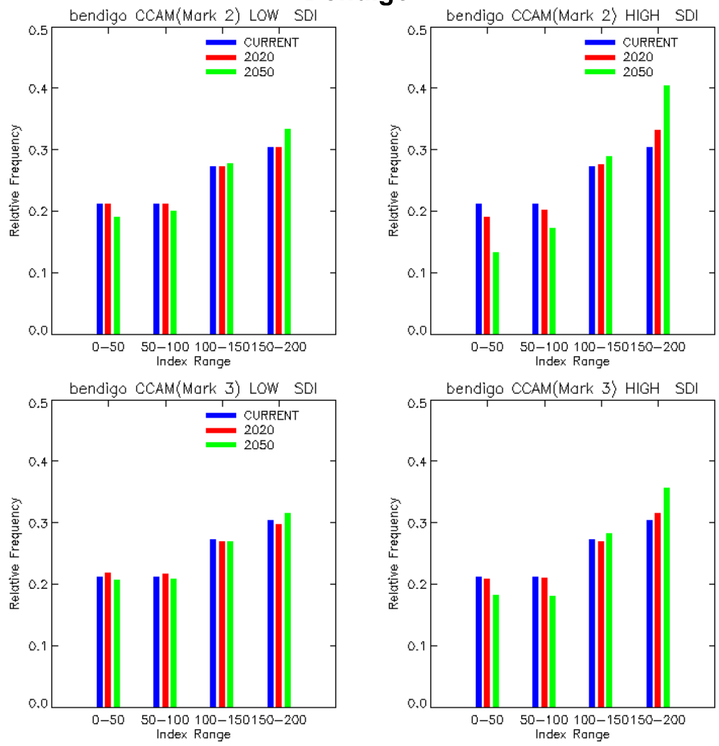
It is important to note that at present, it is not possible to assign probabilities to values within these ranges. However, the IPCC (2001b) defined confidence levels that represent "the degree of belief among the authors in the validity of a conclusion, based on their collective expert judgment of observational evidence, modelling results and theory that they have examined". The confidence levels are:

- Very high (95% or greater);
- High (67-94%);
- Medium (33-66%);
- Low (5-32%);
- Very low (4% or less).

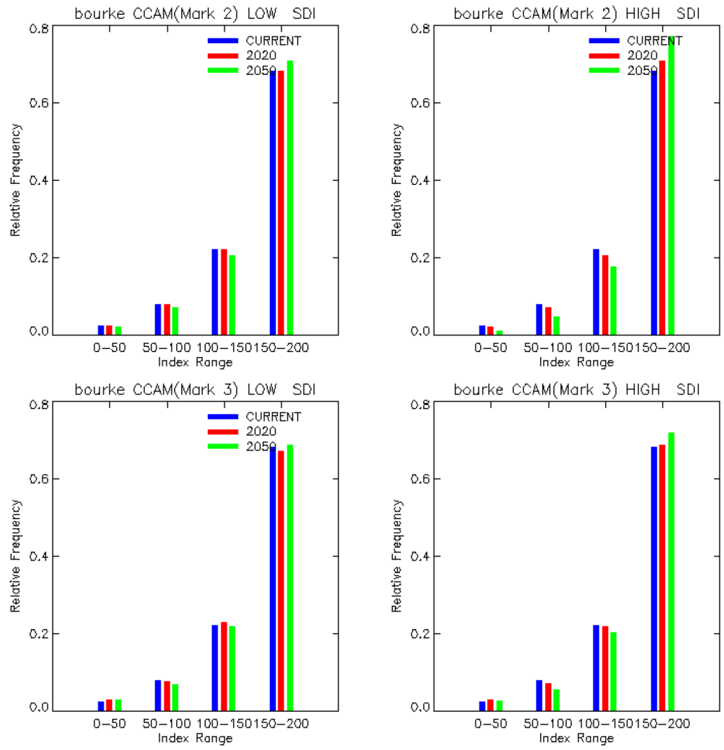
For the global warming data in Figure 1-A1, we have very high confidence that the lower warming limits will be exceeded and that the higher limits will not be exceeded.

Appendix 2: Soil Dryness Index

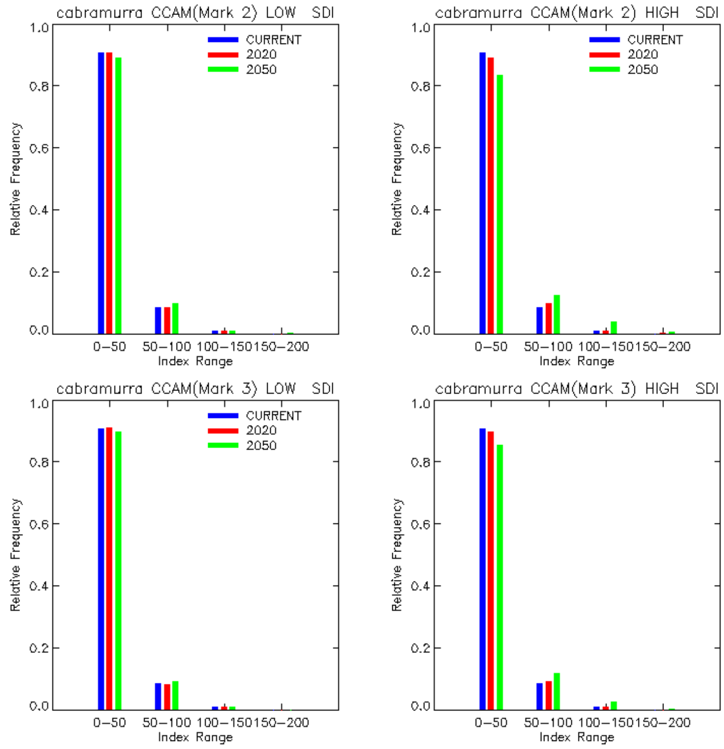
Bendigo



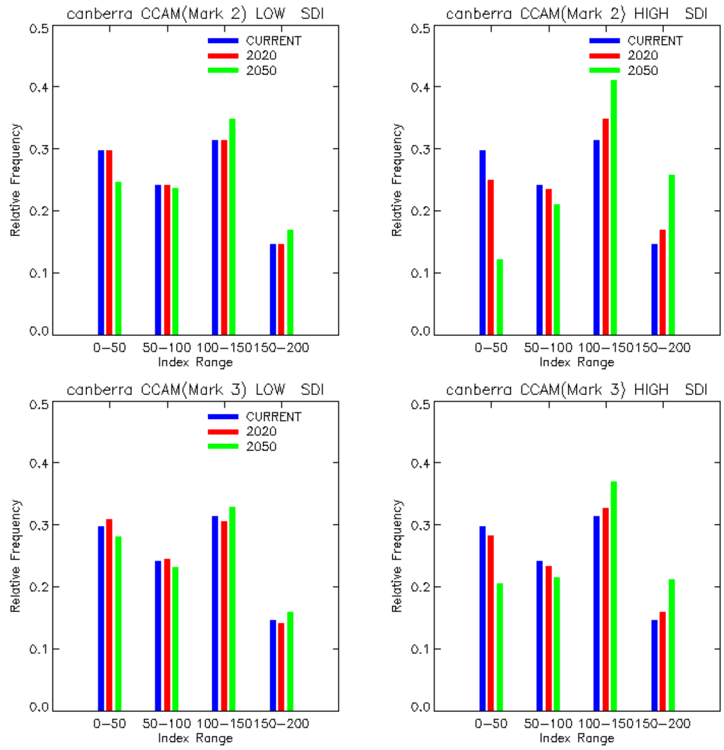
Bourke



Cabramurra



Canberra



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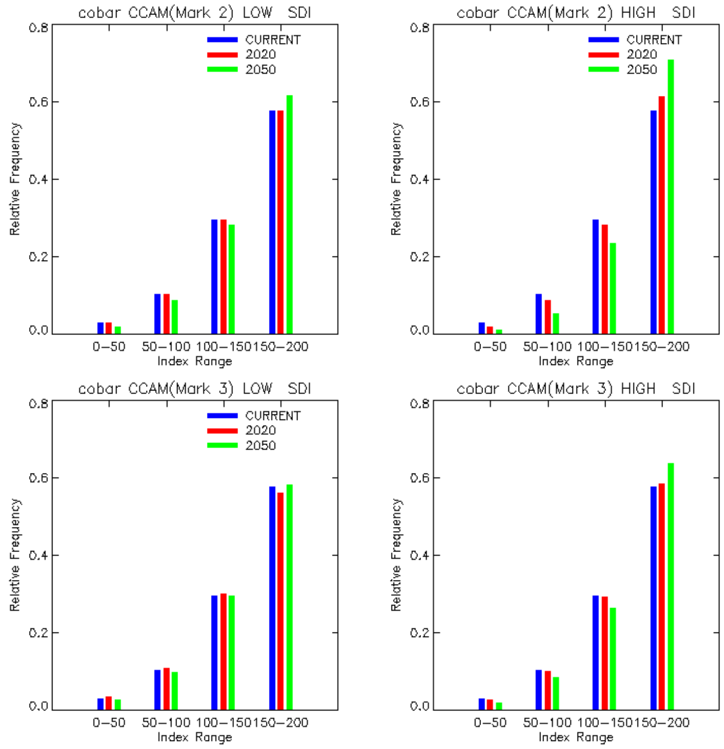

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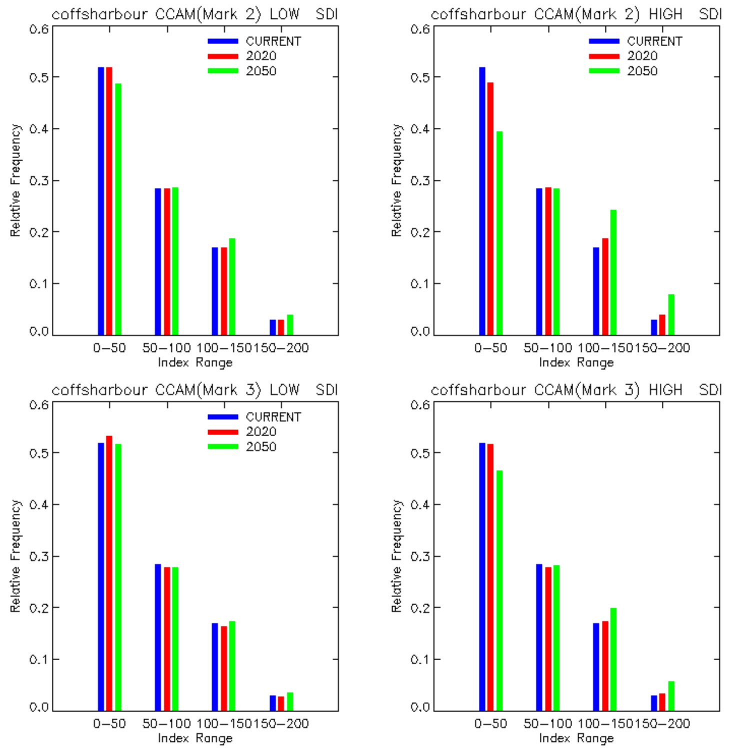
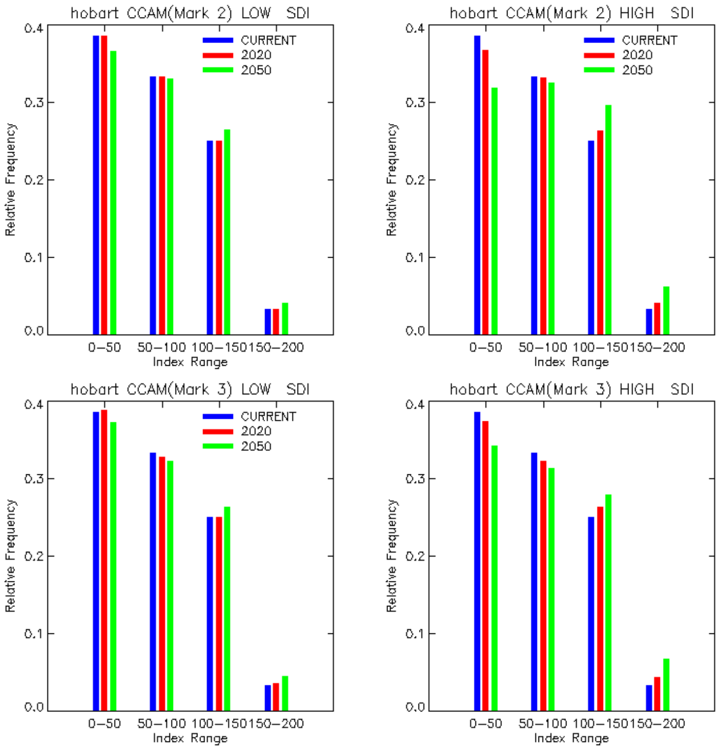
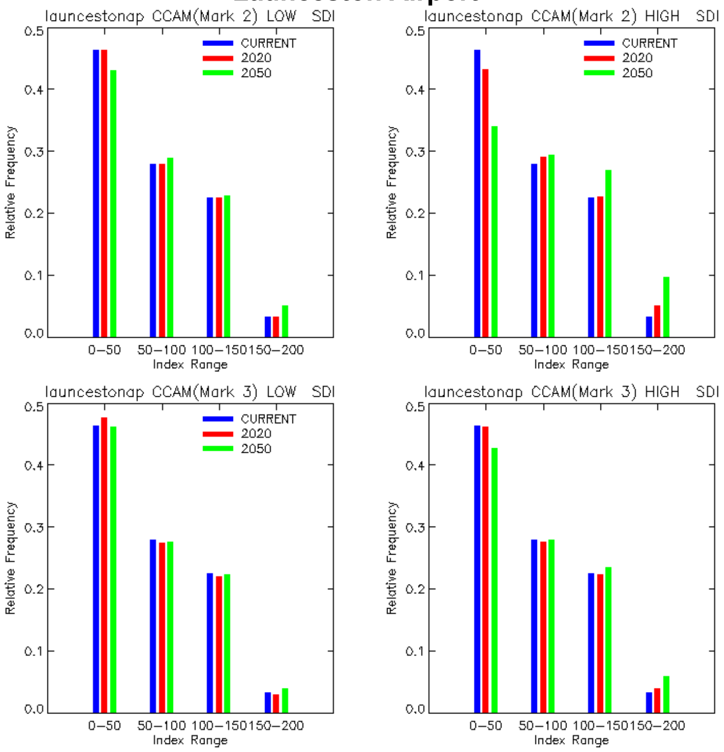
Coffs Harbour



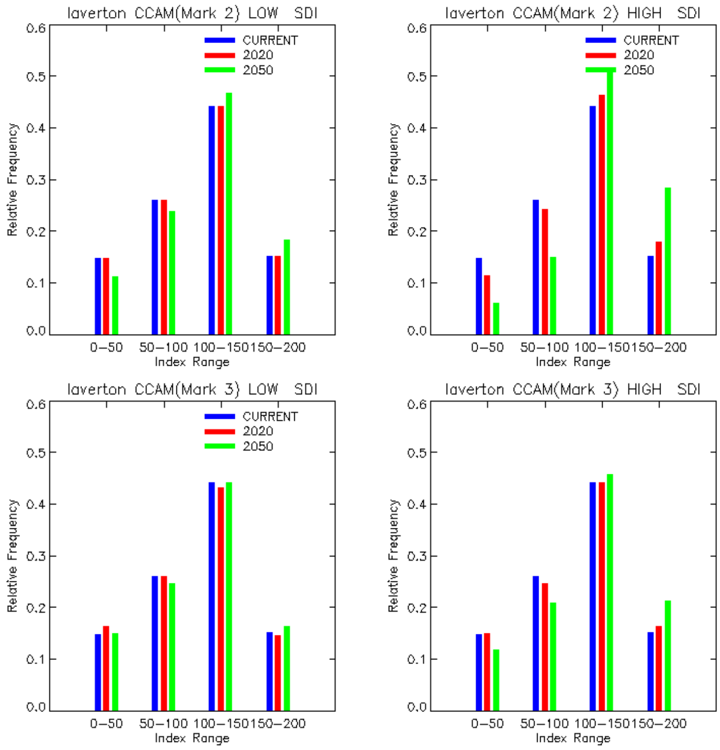
Hobart



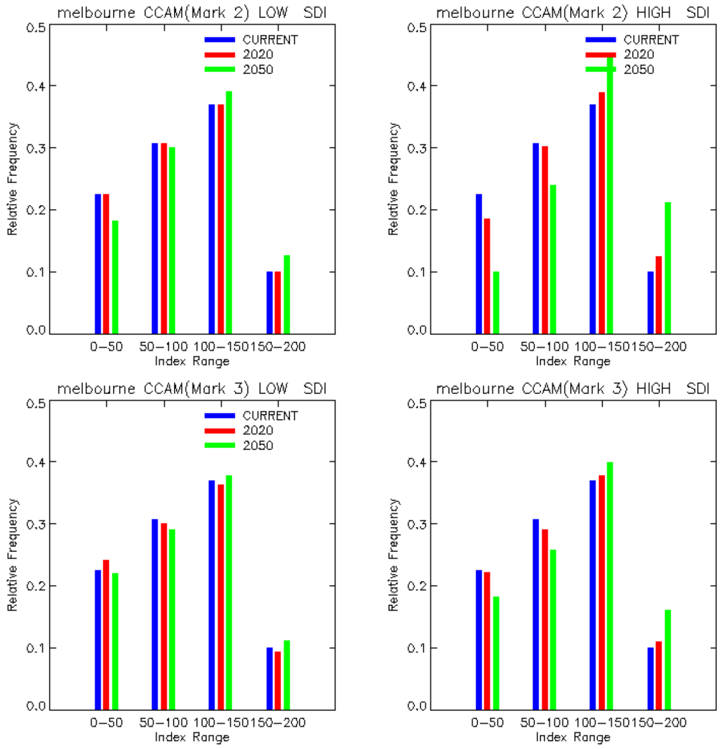
Launceston Airport



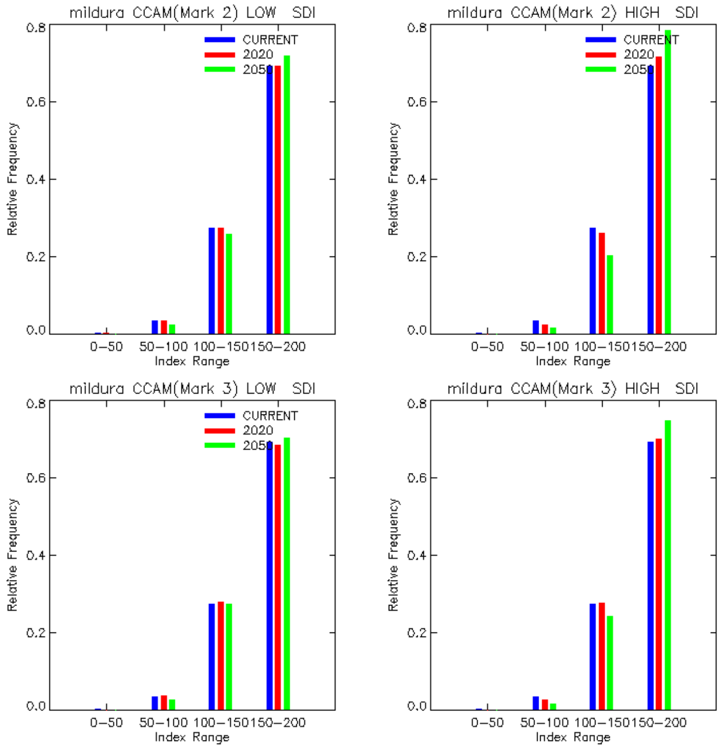
Laverton



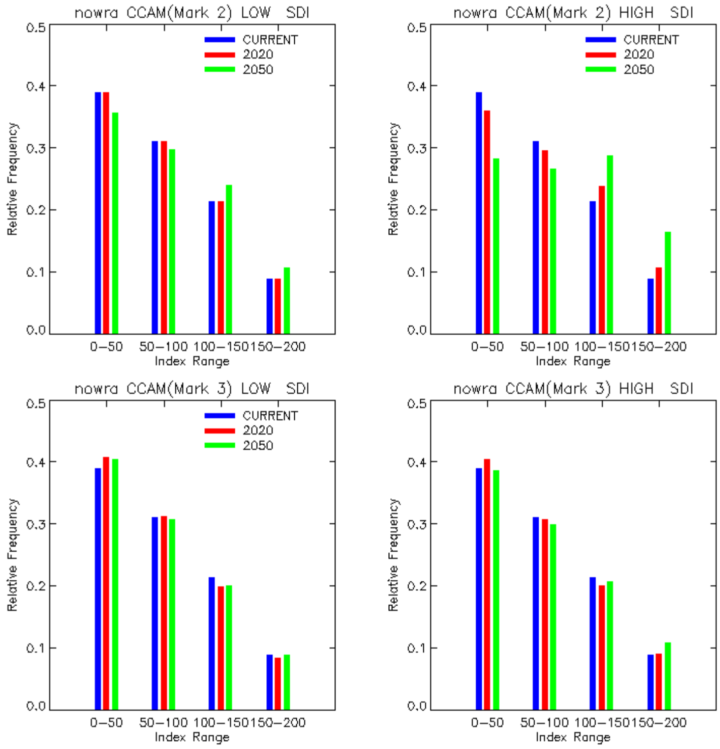
Melbourne



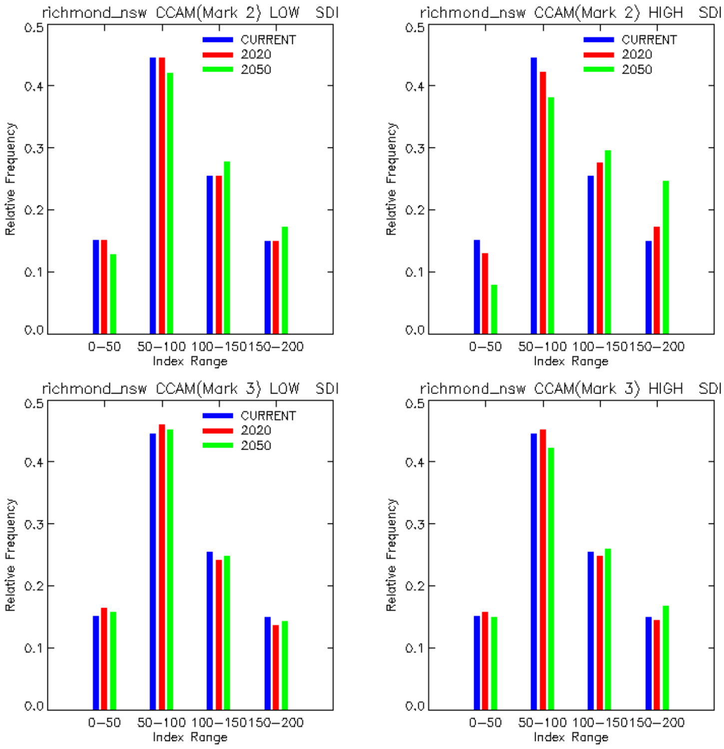
Mildura



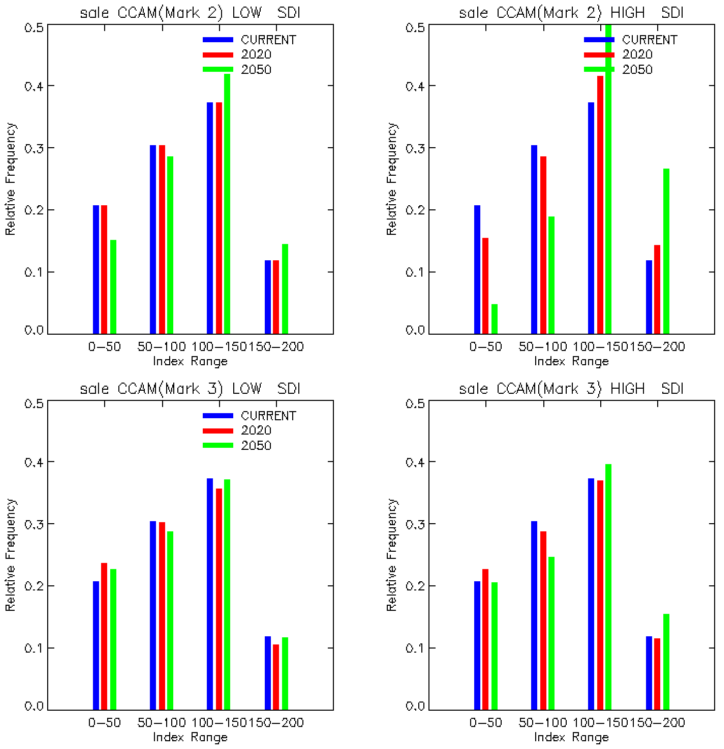
Nowra



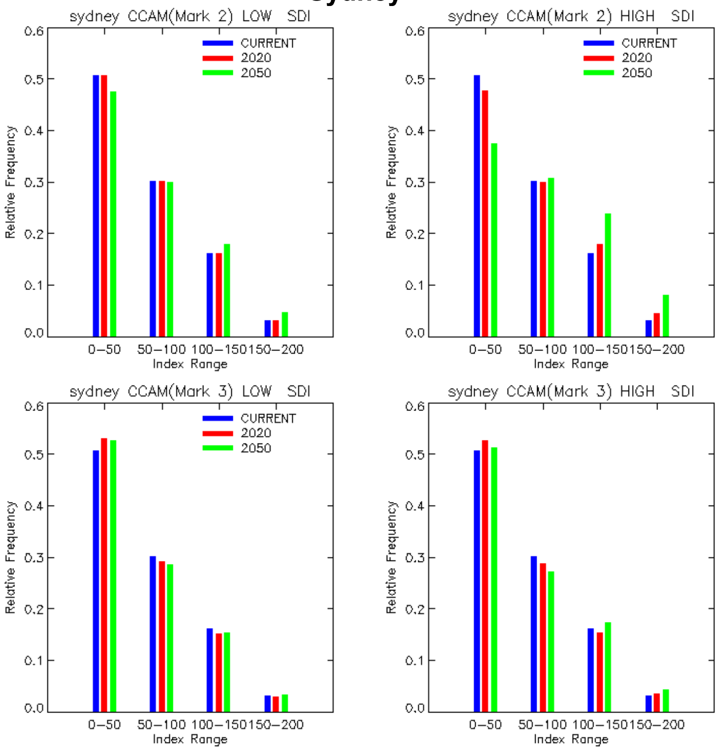
Richmond NSW



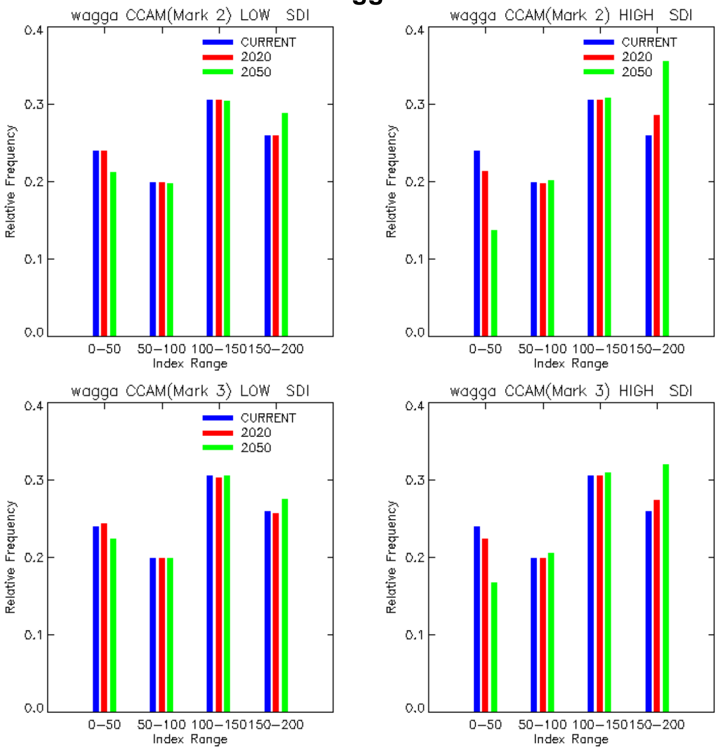
Sale



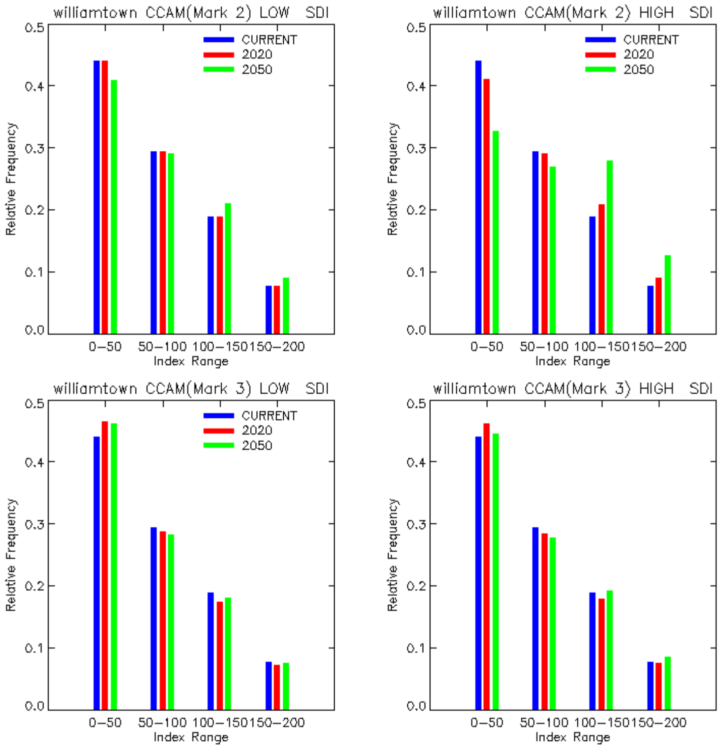
Sydney



Wagga

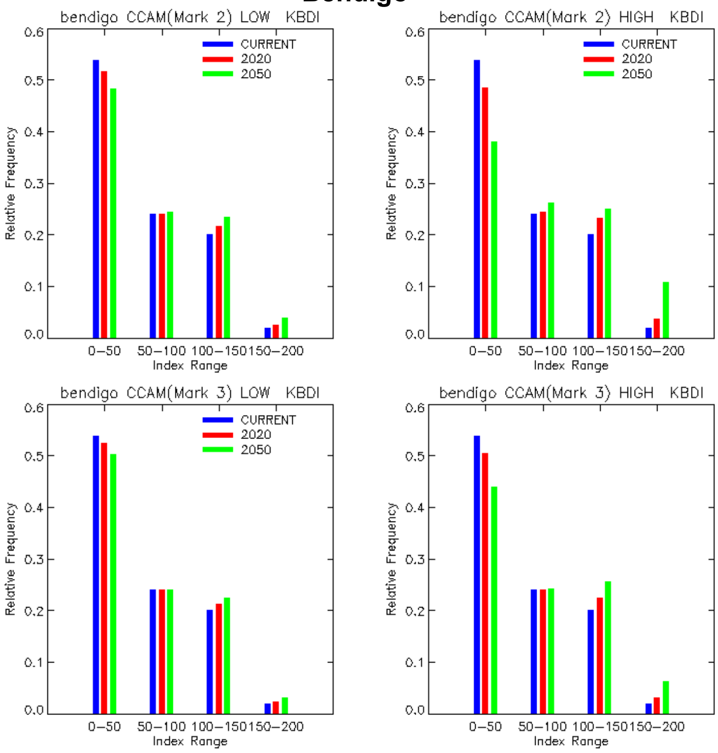


Williamtown

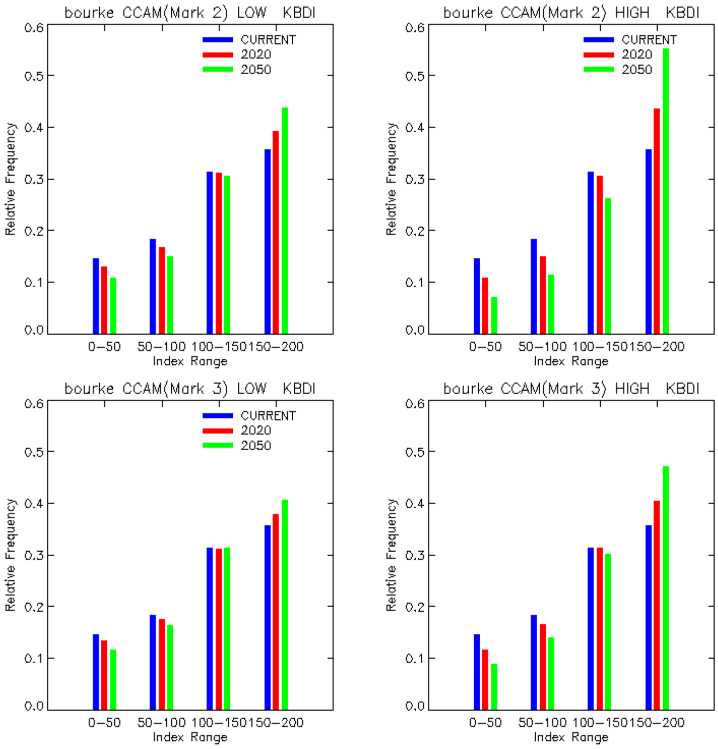


Appendix 3: Keetch Byram Drought Index Index

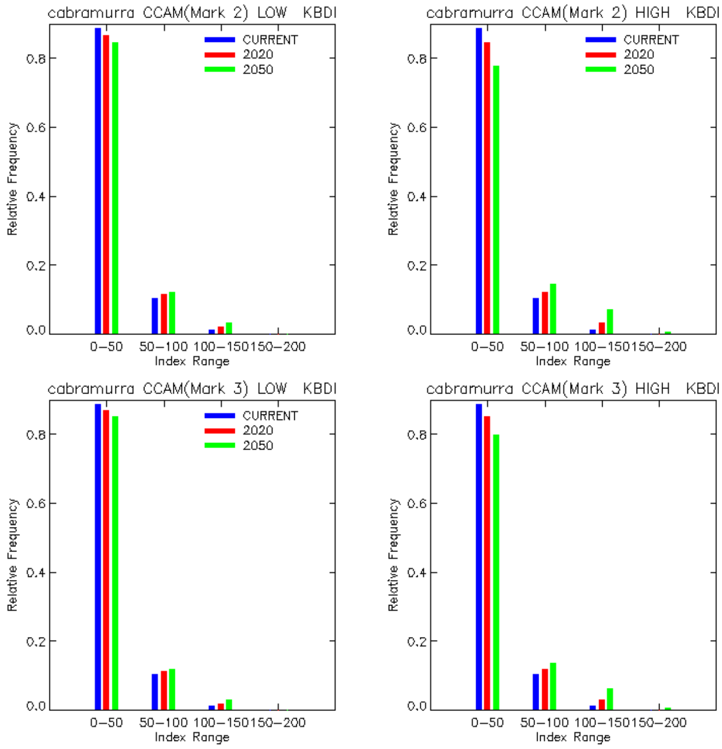
Bendigo



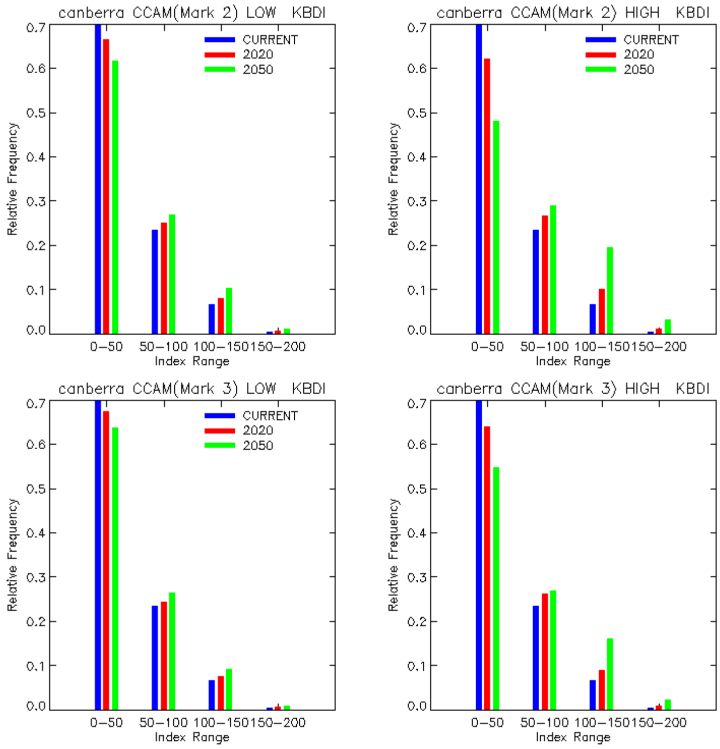
Bourke



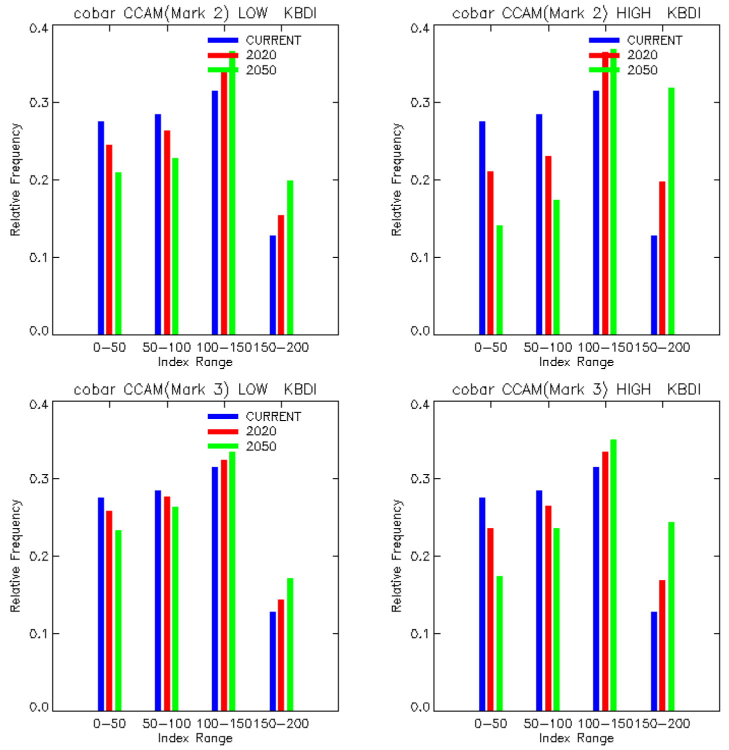
Cabramurra



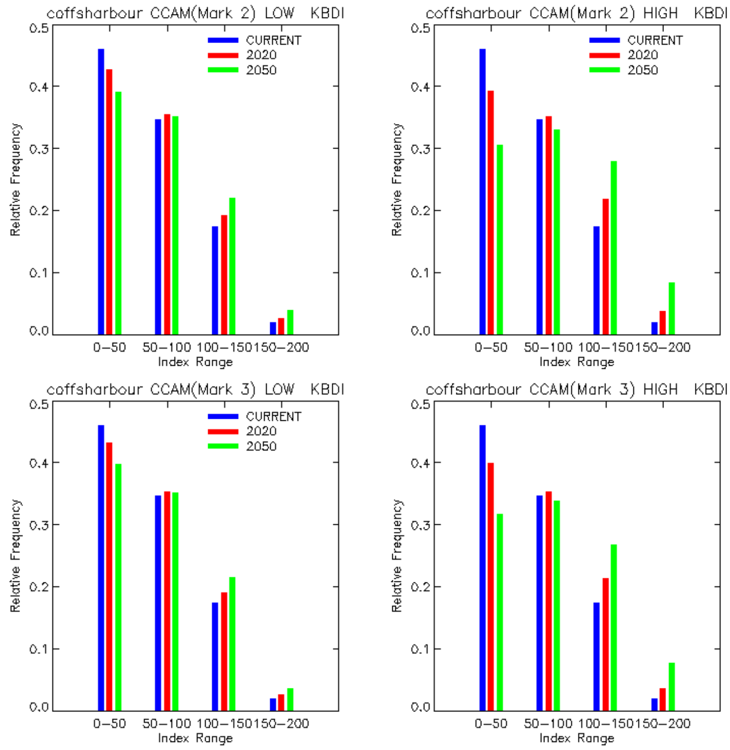
Canberra



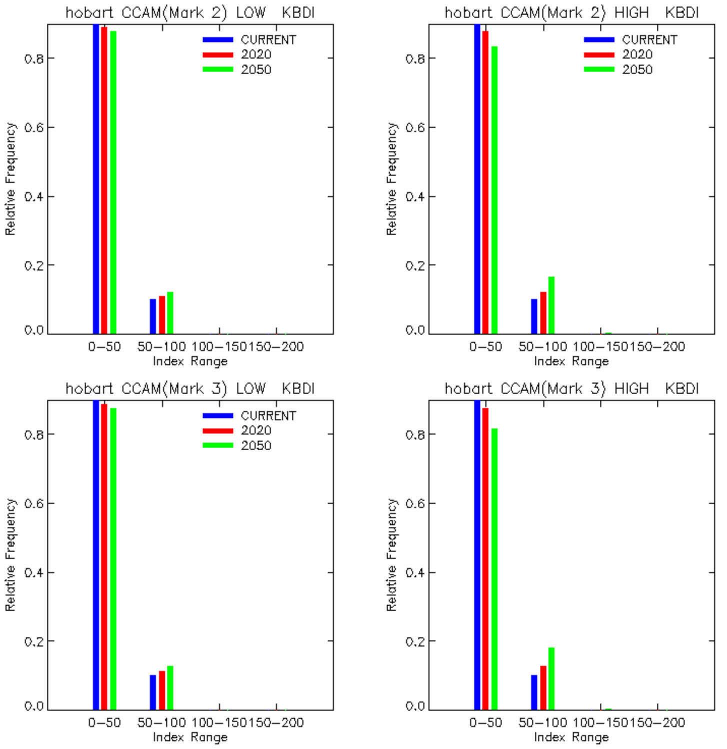
Cobar



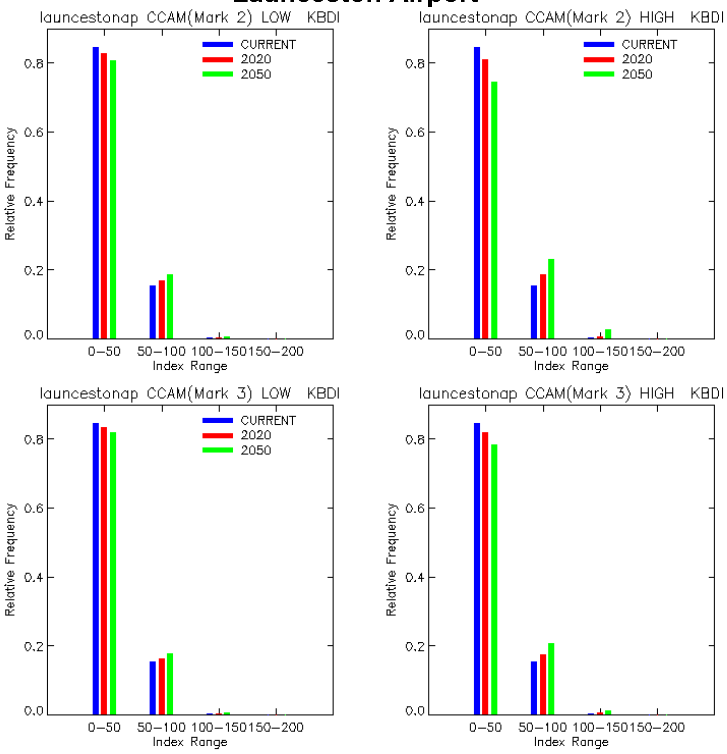
Coffs Harbour



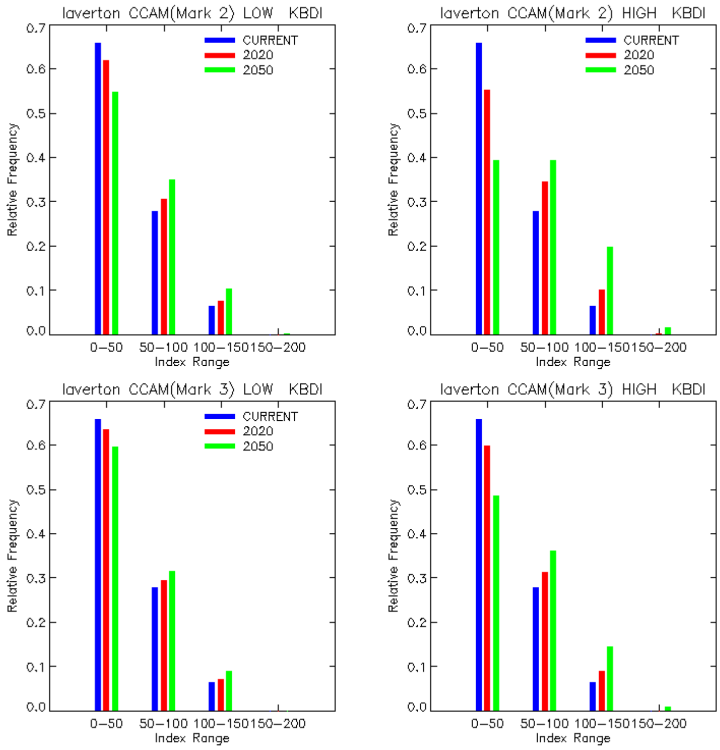
Hobart



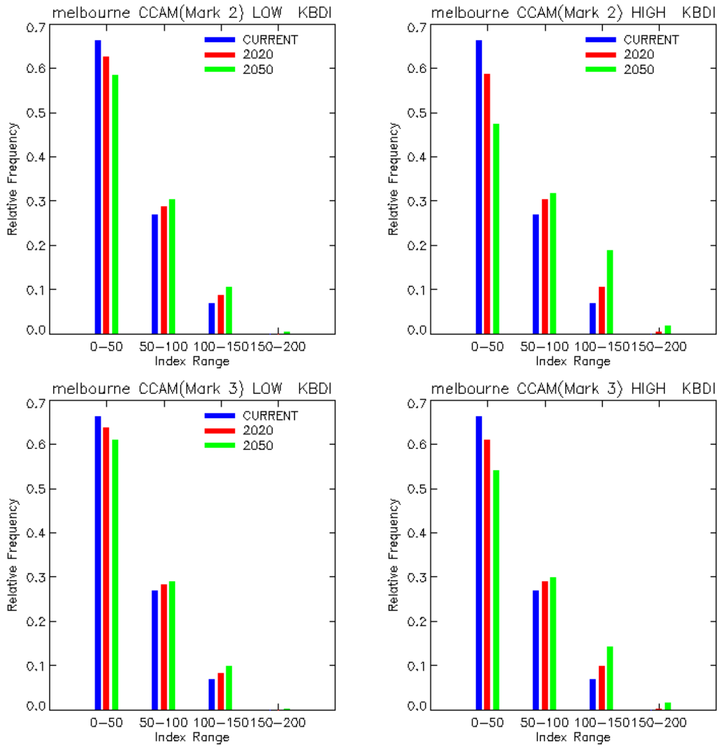
Launceston Airport



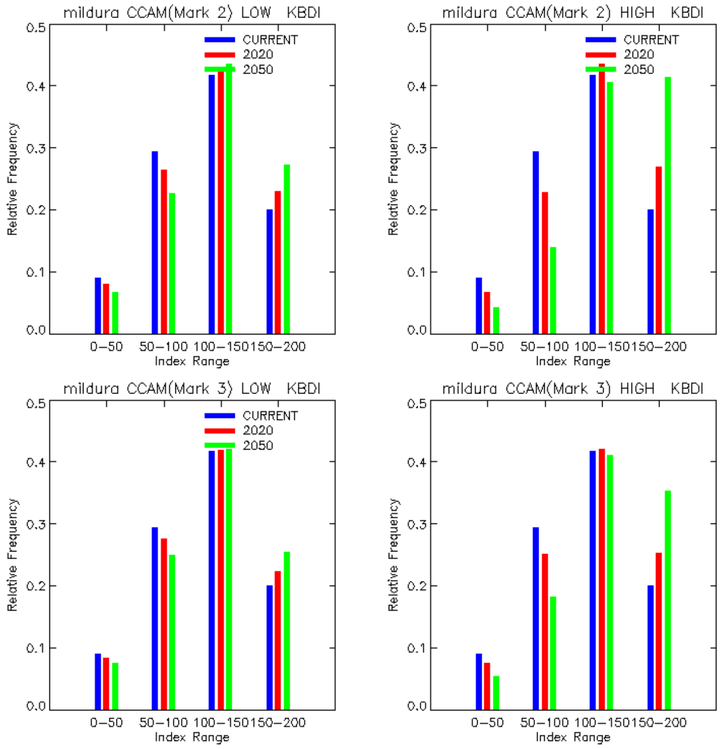
Laverton



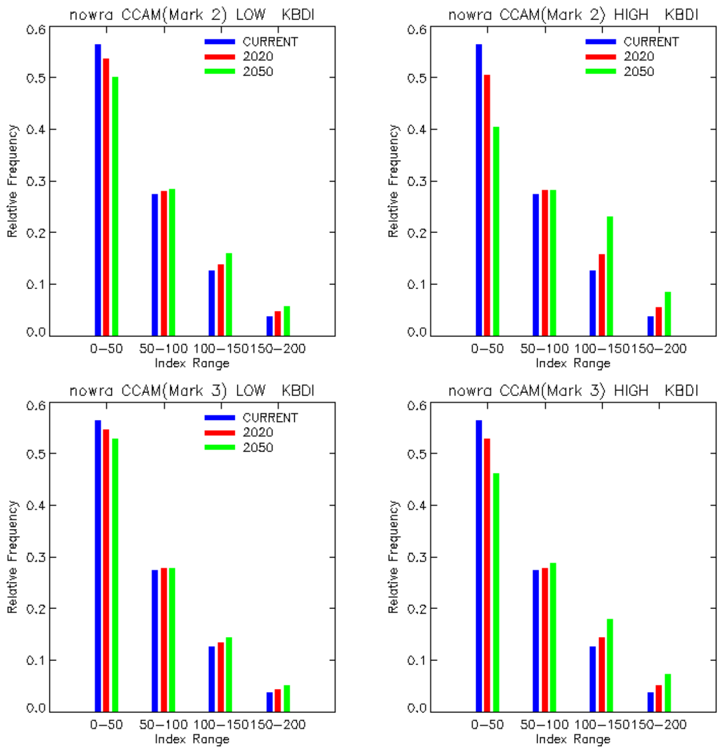
Melbourne



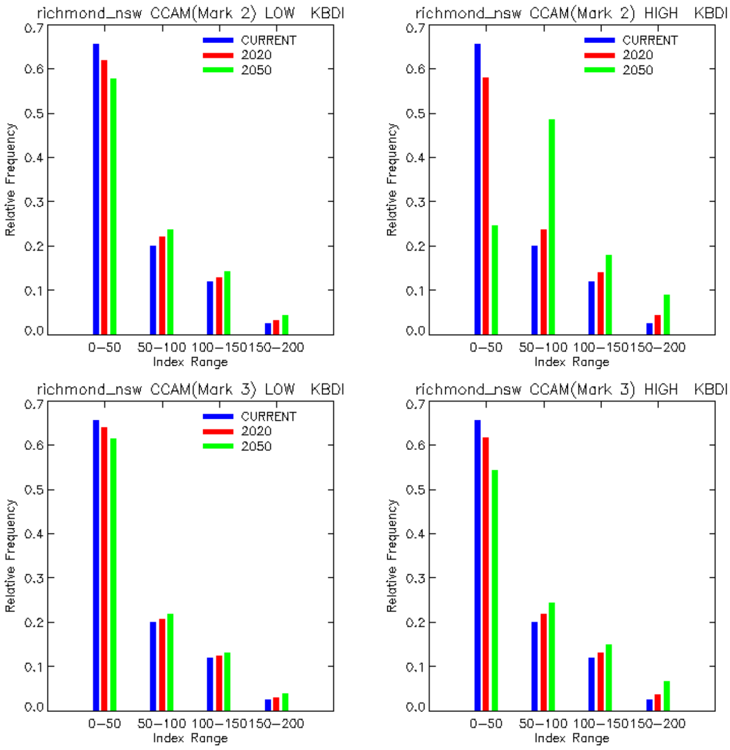
Mildura



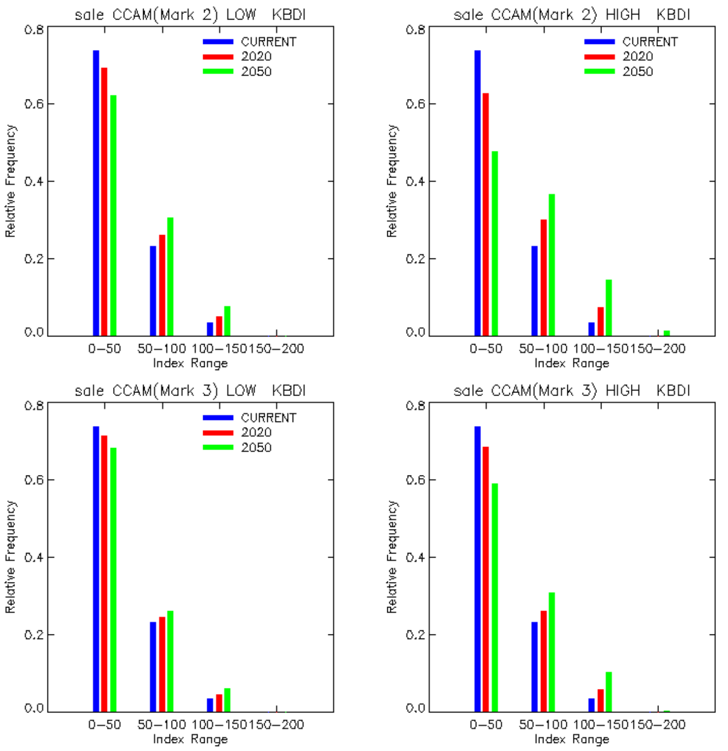
Nowra



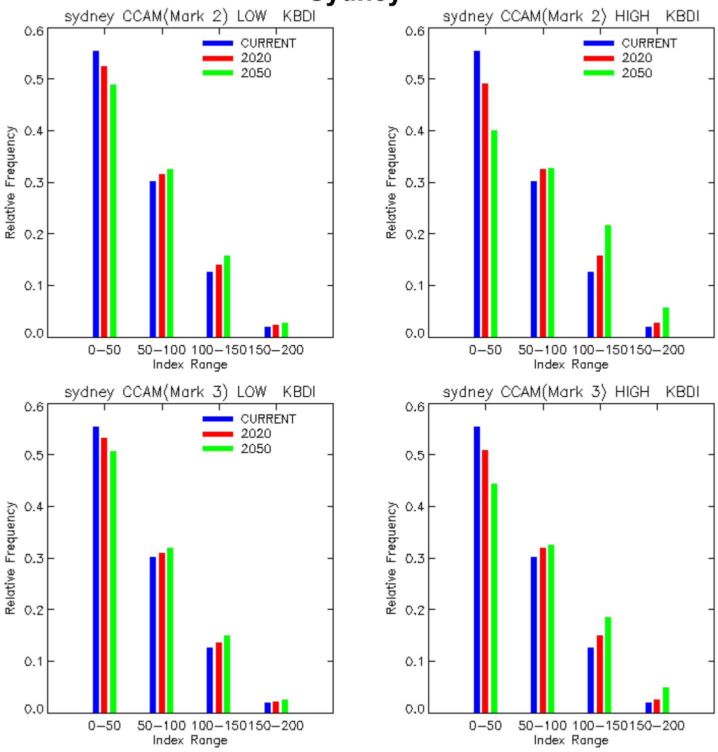
Richmond NSW



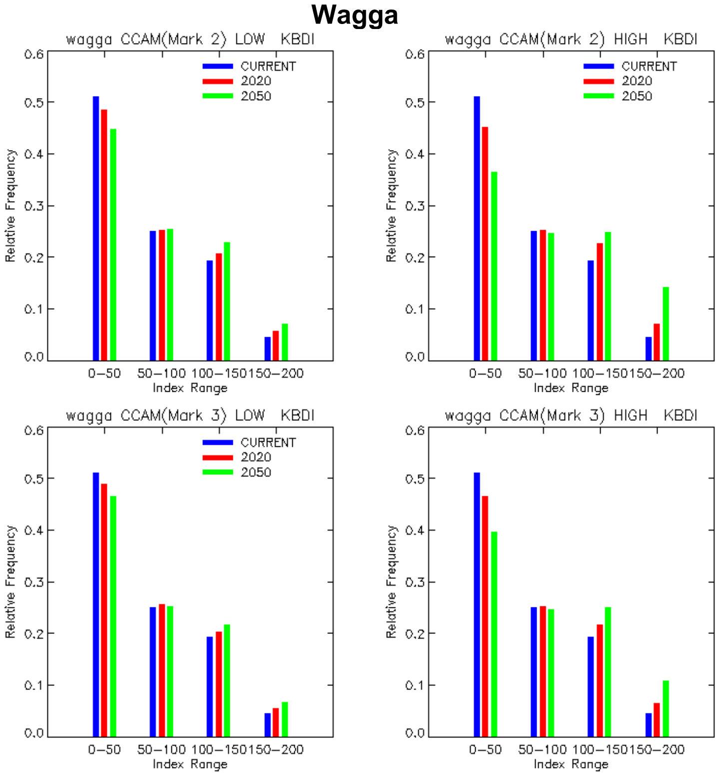
Sale



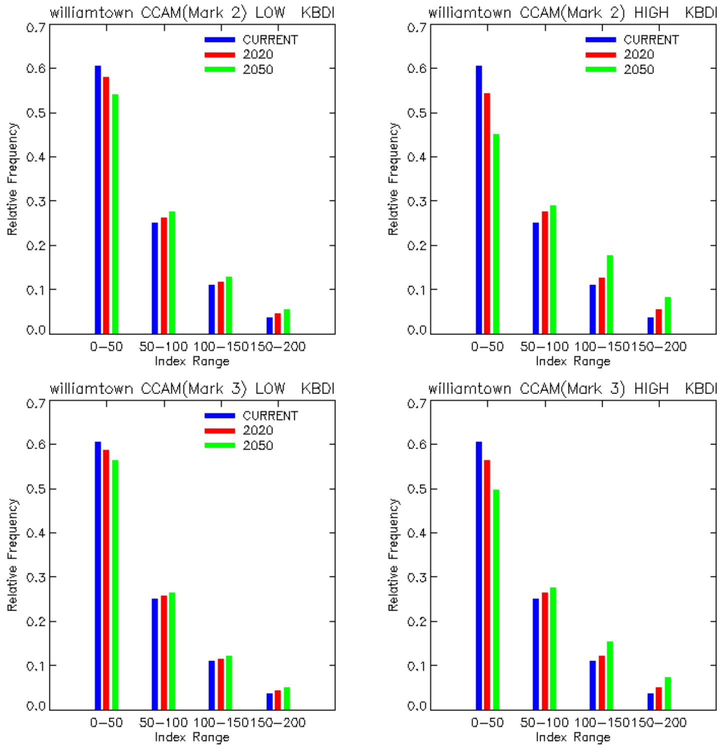
Sydney



Wagga

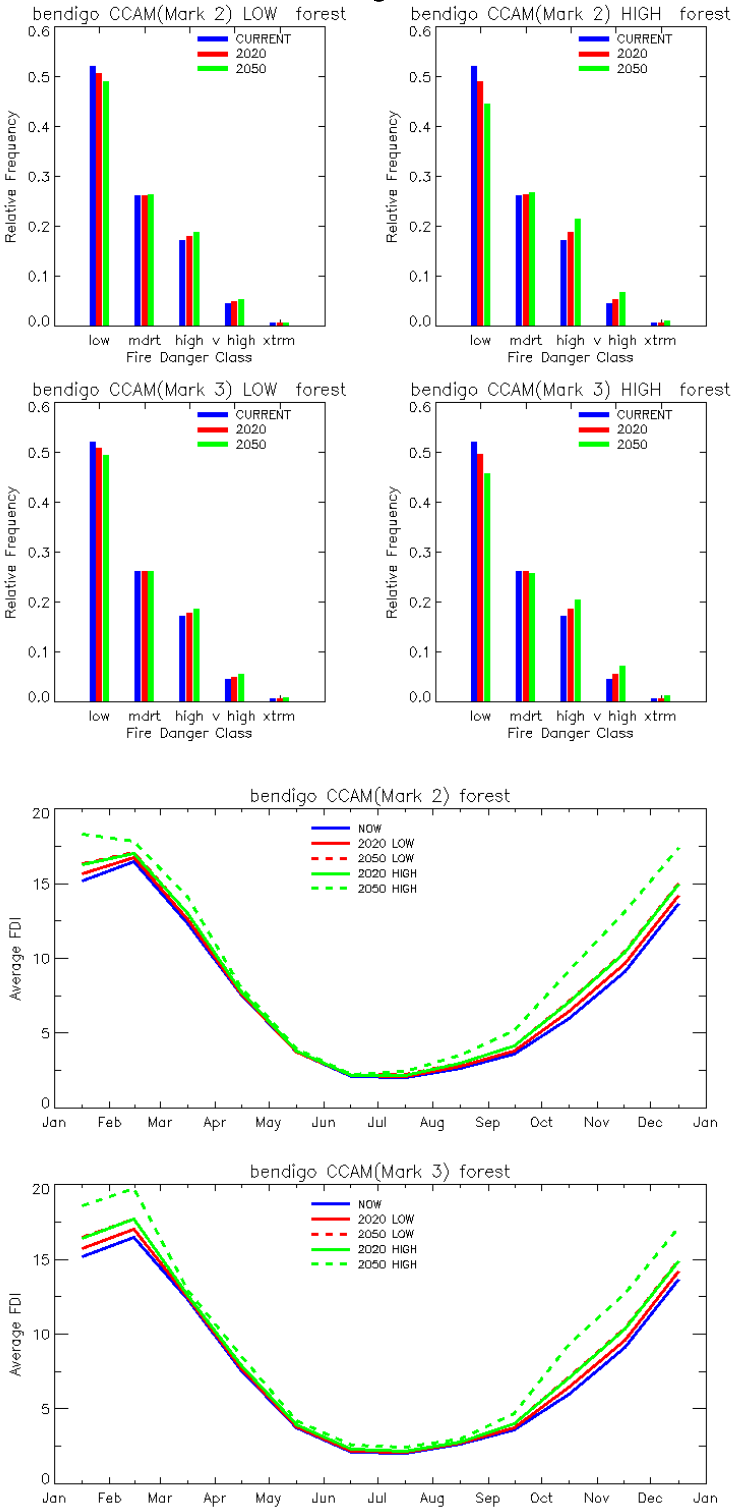


Williamtown

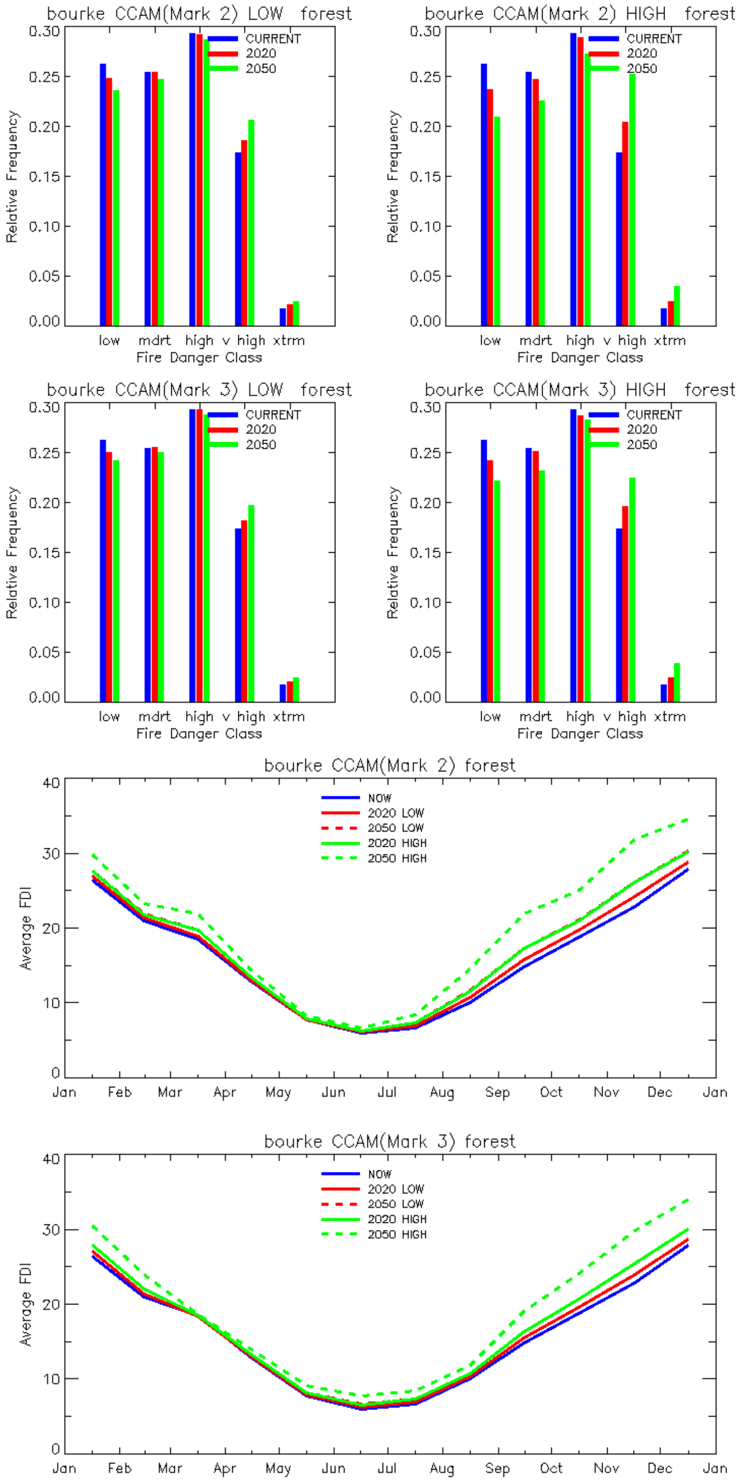


Appendix 4: Forest Fire Danger Index

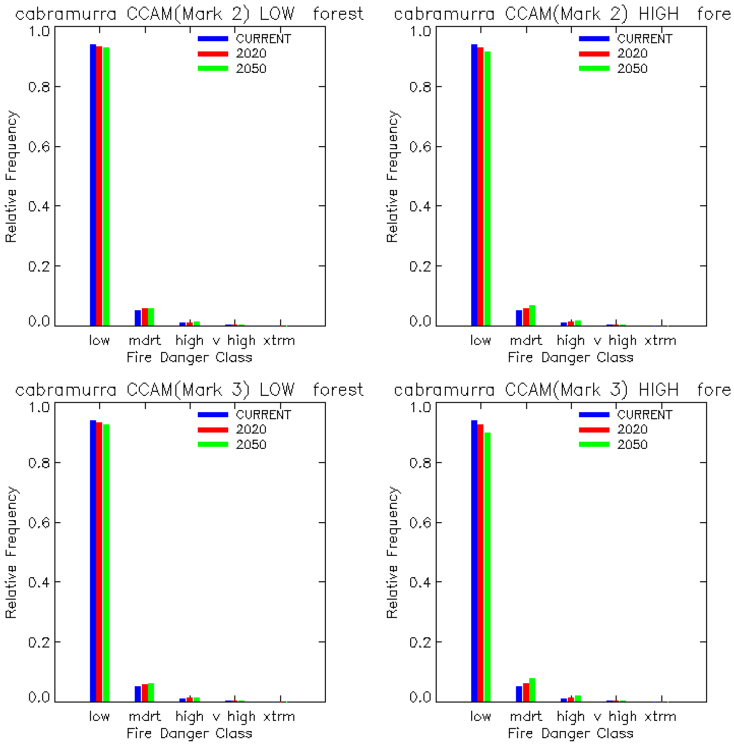
Bendigo



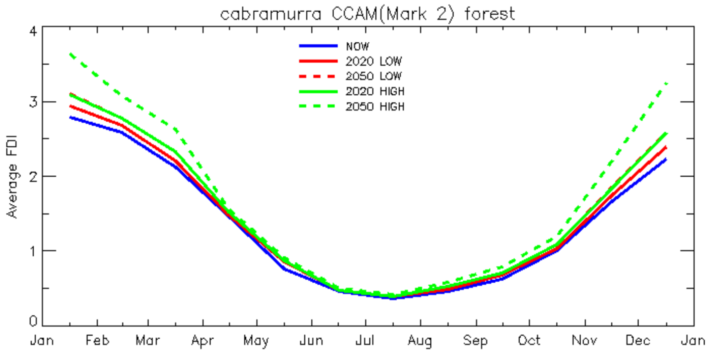
Bourke


bourke CCAM(Mark 2) LOW forest
bourke CCAM(Mark 2) HIGH forest
bourke CCAM(Mark 3) LOW forest
bourke CCAM(Mark 3) HIGH forest
CURRENT
2020
2050
Relative Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
low
mdrt
high
v high
xtrm
Fire Danger Class
bourke CCAM(Mark 2) forest
bourke CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

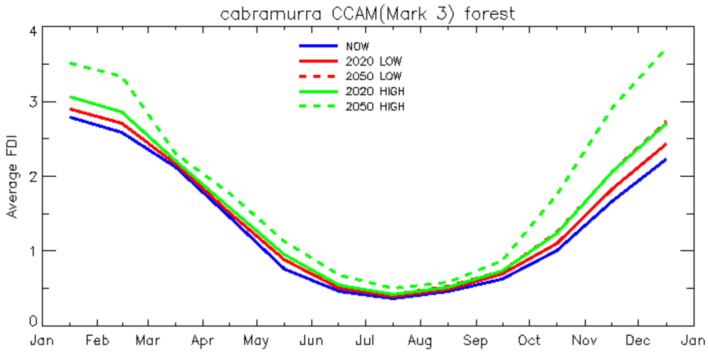
Cabramurra



cabramurra CCAM(Mark 2) LOW forest
cabramurra CCAM(Mark 2) HIGH fore
cabramurra CCAM(Mark 3) LOW forest
cabramurra CCAM(Mark 3) HIGH fore
CURRENT
2020
2050
Relative Frequency
0.0
0.2
0.4
0.6
0.8
1.0
low
mdrt
high
v high
xtrm
Fire Danger Class

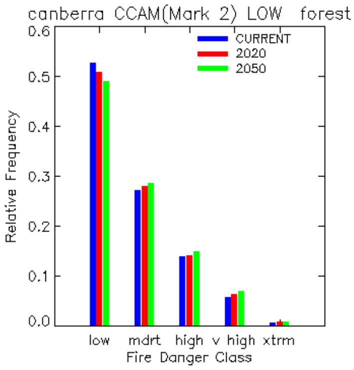


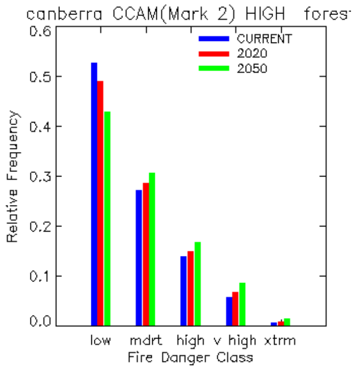
cabramurra CCAM(Mark 2) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
1
2
3
4
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

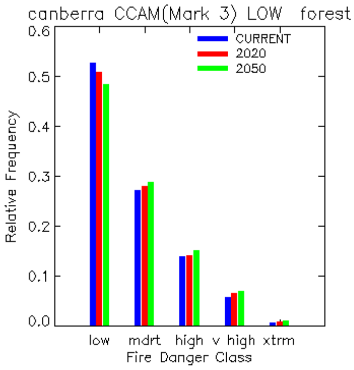


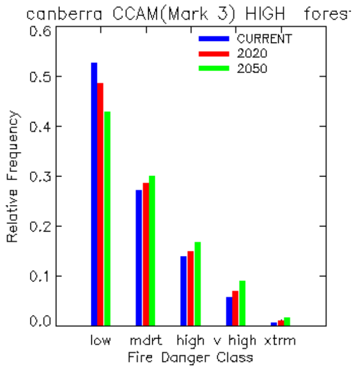
cabramurra CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
1
2
3
4
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

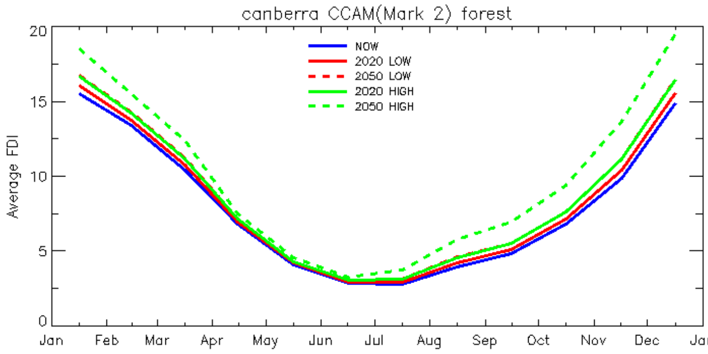
Canberra

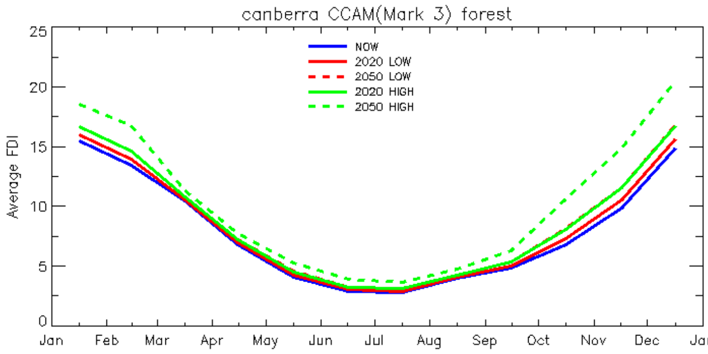

canberra CCAM(Mark 2) LOW forest
CURRENT
2020
2050
Relative Frequency
0.6
0.5
0.4
0.3
0.2
0.1
0.0
low
mdrt
high
v high
xtrm
Fire Danger Class


canberra CCAM(Mark 2) HIGH fores
CURRENT
2020
2050
Relative Frequency
0.6
0.5
0.4
0.3
0.2
0.1
0.0
low
mdrt
high
v high
xtrm
Fire Danger Class

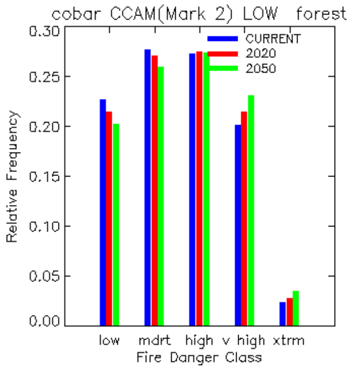

canberra CCAM(Mark 3) LOW forest
CURRENT
2020
2050
Relative Frequency
0.6
0.5
0.4
0.3
0.2
0.1
0.0
low
mdrt
high
v high
xtrm
Fire Danger Class

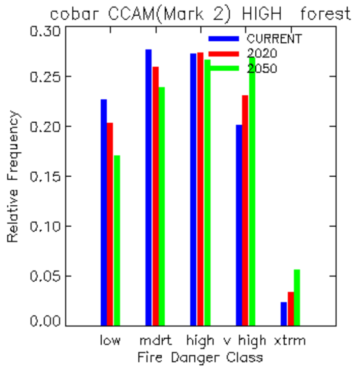

canberra CCAM(Mark 3) HIGH fores
CURRENT
2020
2050
Relative Frequency
0.6
0.5
0.4
0.3
0.2
0.1
0.0
low
mdrt
high
v high
xtrm
Fire Danger Class

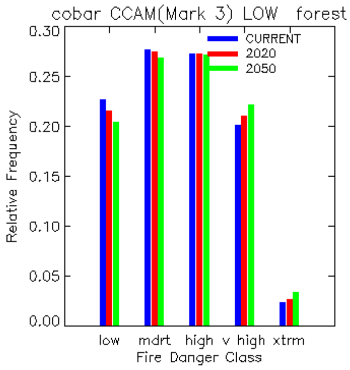

canberra CCAM(Mark 2) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

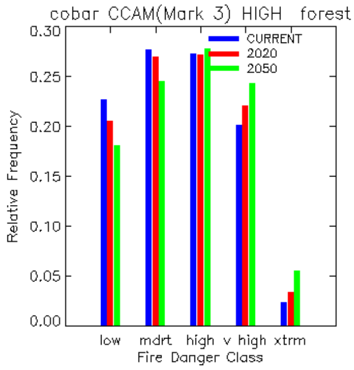

canberra CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

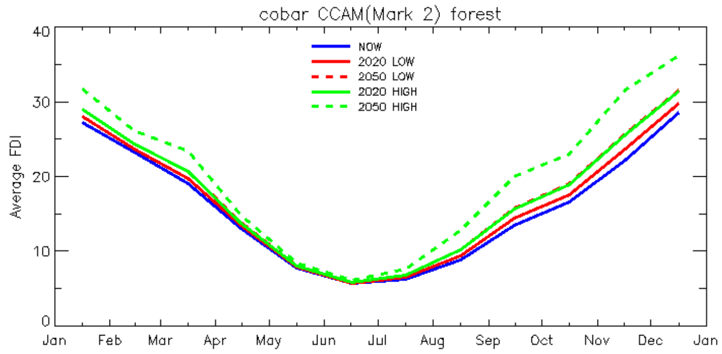
Cobar


cobar CCAM(Mark 2) LOW forest
CURRENT
2020
2050
Relative Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
low
mdrt
high
v high
xtrm
Fire Danger Class


cobar CCAM(Mark 2) HIGH forest
CURRENT
2020
2050
Relative Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
low
mdrt
high
v high
xtrm
Fire Danger Class


cobar CCAM(Mark 3) LOW forest
CURRENT
2020
2050
Relative Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
low
mdrt
high
v high
xtrm
Fire Danger Class


cobar CCAM(Mark 3) HIGH forest
CURRENT
2020
2050
Relative Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
low
mdrt
high
v high
xtrm
Fire Danger Class


cobar CCAM(Mark 2) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
30
40
Jan
Feb
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May
Jun
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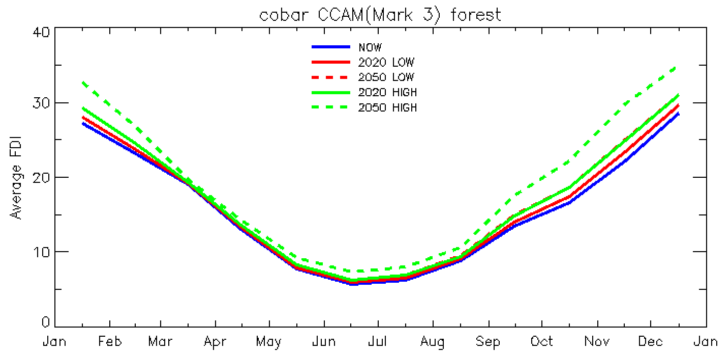
Oct
Nov
Dec
Jan


cobar CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
30
40
Jan
Feb
Mar
Apr
May
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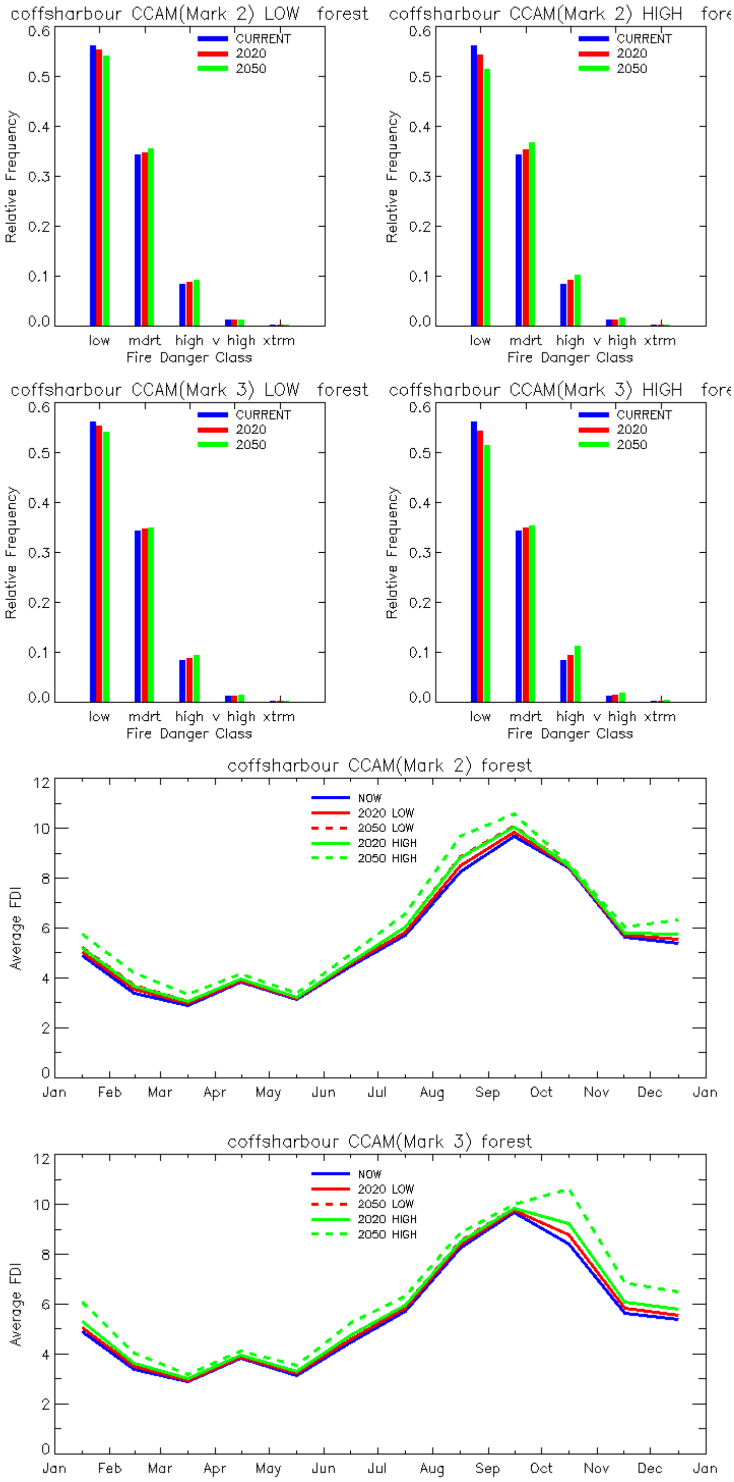
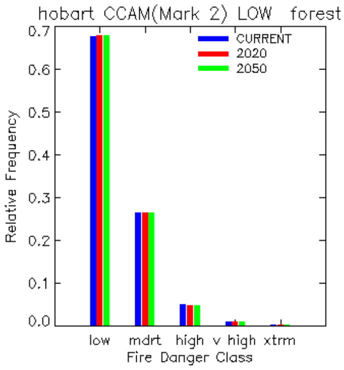
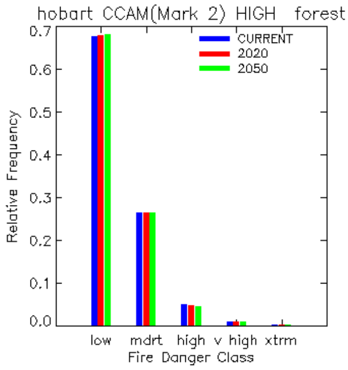
Aug
Sep
Oct
Nov
Dec
Jan

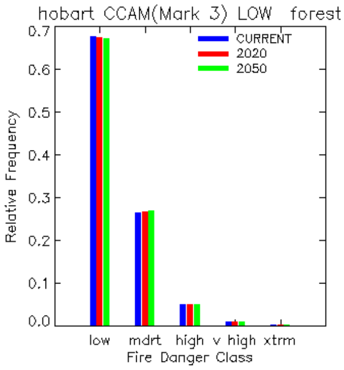
Coffs Harbour

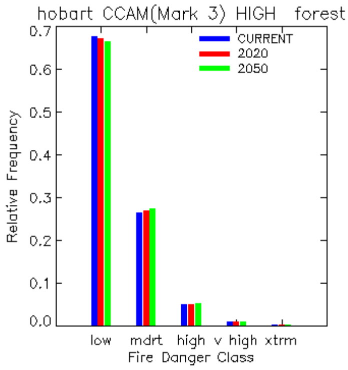


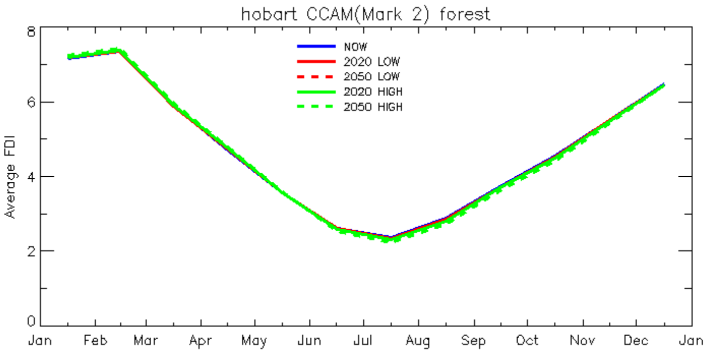
Hobart

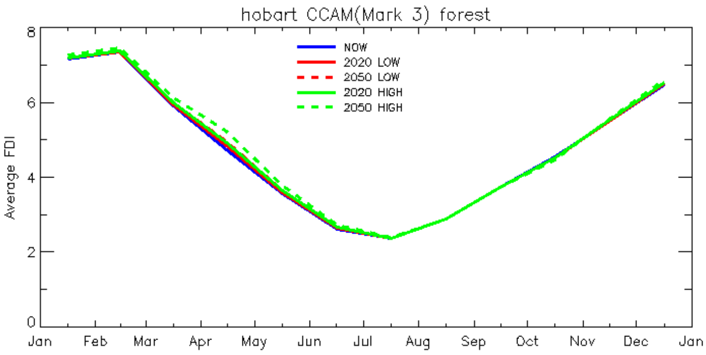

hobart CCAM(Mark 2) LOW forest
CURRENT
2020
2050
Relative Frequency
low mdrt high v high xtrm
Fire Danger Class


hobart CCAM(Mark 2) HIGH forest
CURRENT
2020
2050
Relative Frequency
low mdrt high v high xtrm
Fire Danger Class

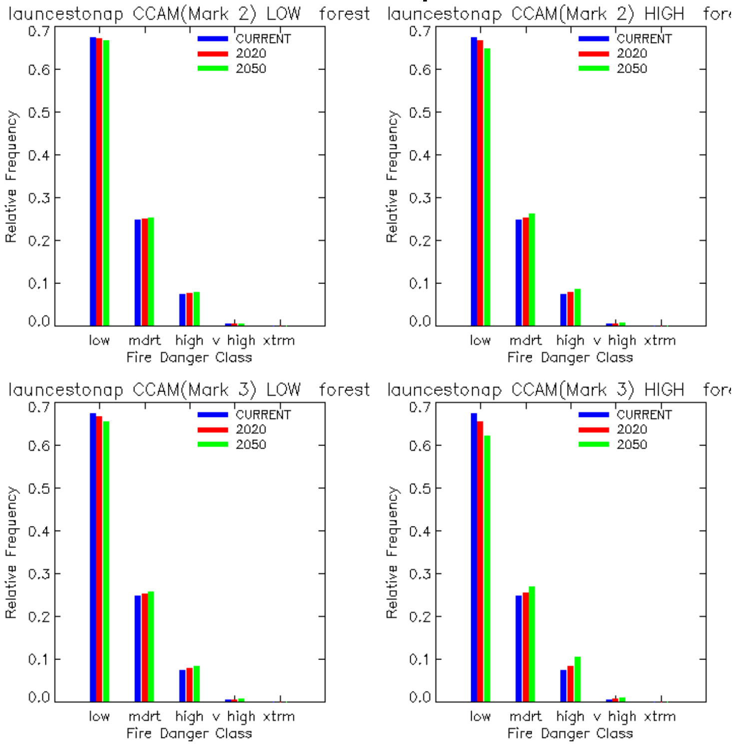

hobart CCAM(Mark 3) LOW forest
CURRENT
2020
2050
Relative Frequency
low mdrt high v high xtrm
Fire Danger Class

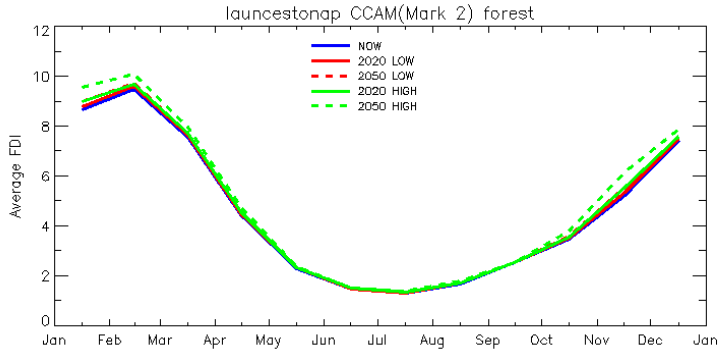

hobart CCAM(Mark 3) HIGH forest
CURRENT
2020
2050
Relative Frequency
low mdrt high v high xtrm
Fire Danger Class

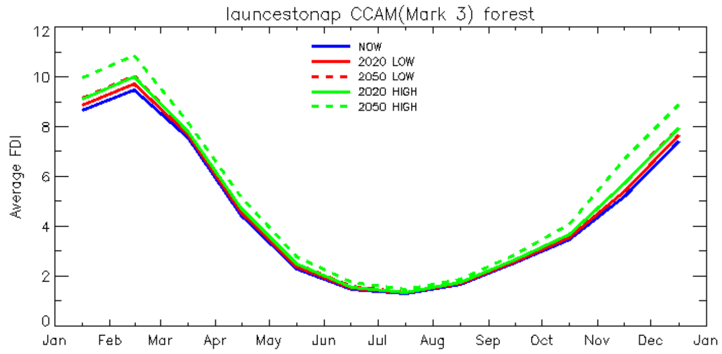

hobart CCAM(Mark 2) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan


hobart CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

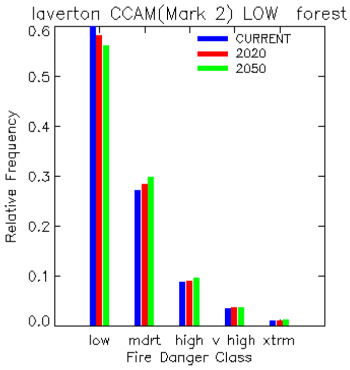
Launceston Airport

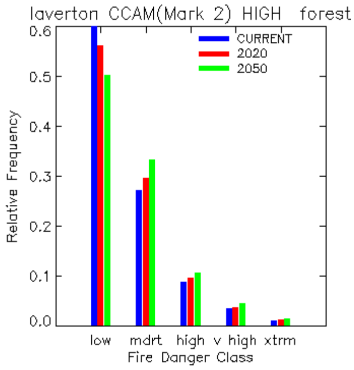


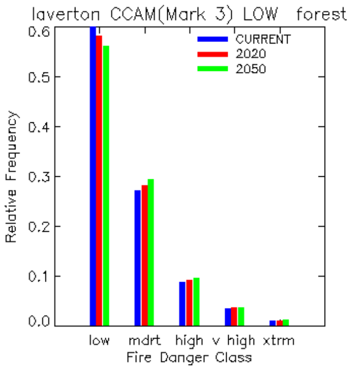


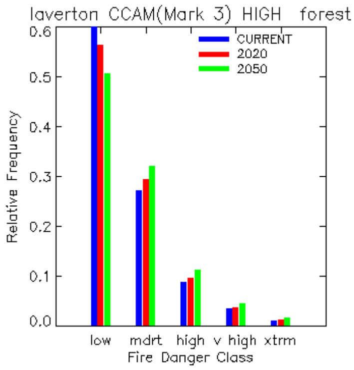


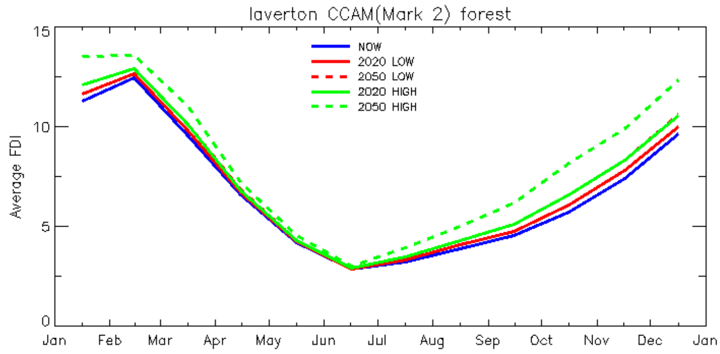
Laverton

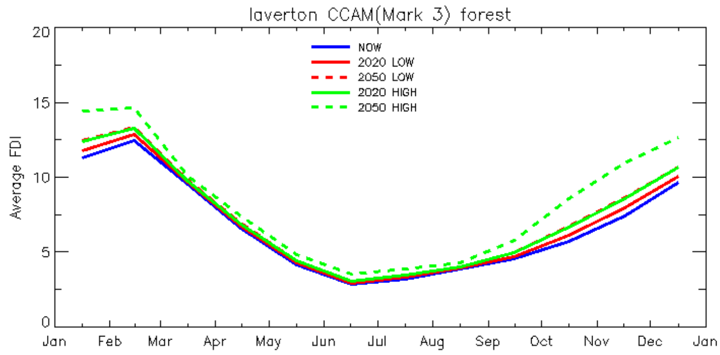

laverton CCAM(Mark 2) LOW forest
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
low
mdrt
high
v high
xtrm
Fire Danger Class


laverton CCAM(Mark 2) HIGH forest
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
low
mdrt
high
v high
xtrm
Fire Danger Class

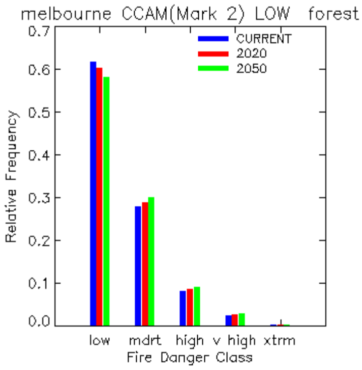

laverton CCAM(Mark 3) LOW forest
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
low
mdrt
high
v high
xtrm
Fire Danger Class

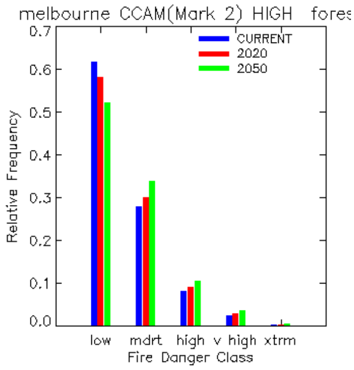

laverton CCAM(Mark 3) HIGH forest
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
low
mdrt
high
v high
xtrm
Fire Danger Class

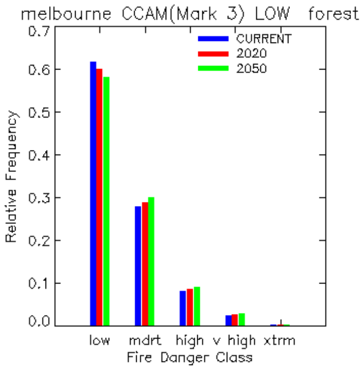

laverton CCAM(Mark 2) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
5
10
15
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

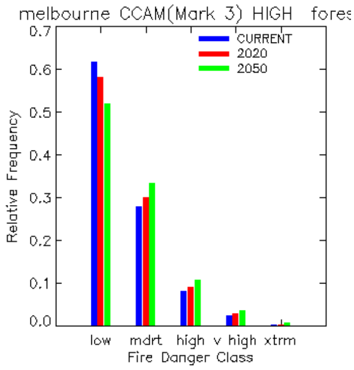

laverton CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
5
10
15
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

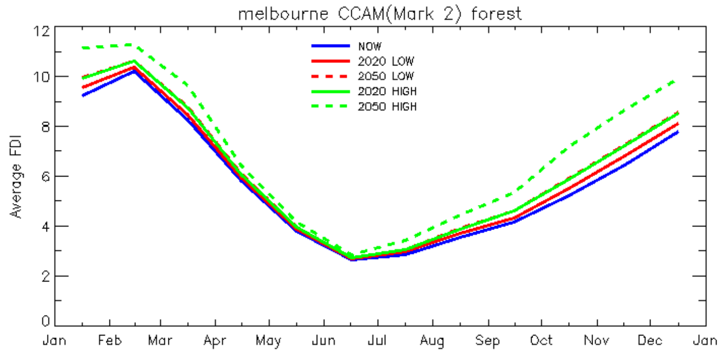
Melbourne

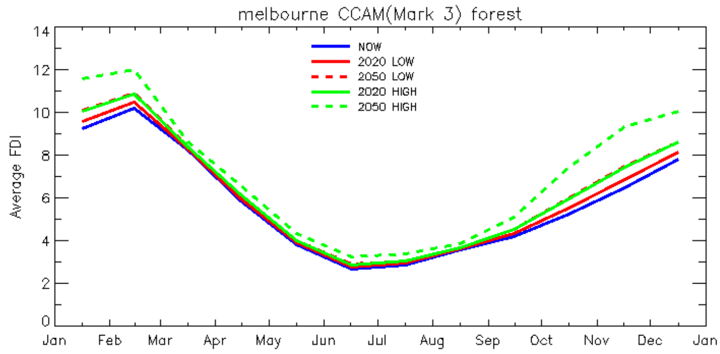

melbourne CCAM(Mark 2) LOW forest
CURRENT
2020
2050
Relative Frequency
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
low mdrt high v high xtrm
Fire Danger Class


melbourne CCAM(Mark 2) HIGH fores
CURRENT
2020
2050
Relative Frequency
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
low mdrt high v high xtrm
Fire Danger Class

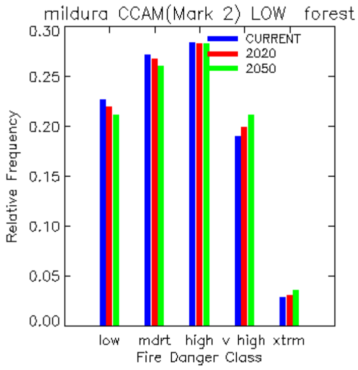

melbourne CCAM(Mark 3) LOW forest
CURRENT
2020
2050
Relative Frequency
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
low mdrt high v high xtrm
Fire Danger Class


melbourne CCAM(Mark 3) HIGH fores
CURRENT
2020
2050
Relative Frequency
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
low mdrt high v high xtrm
Fire Danger Class

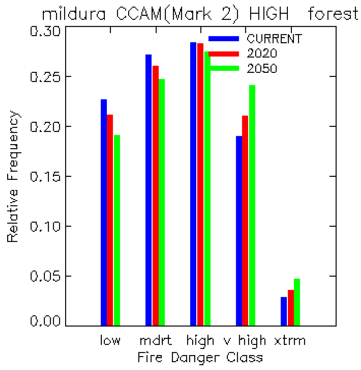

melbourne CCAM(Mark 2) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0 2 4 6 8 10 12
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan


melbourne CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0 2 4 6 8 10 12 14
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

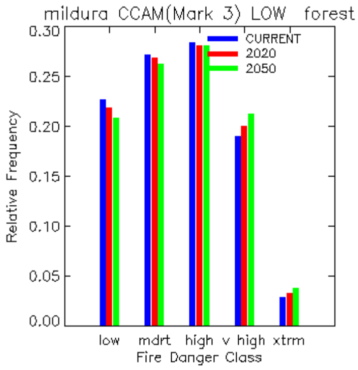
Mildura



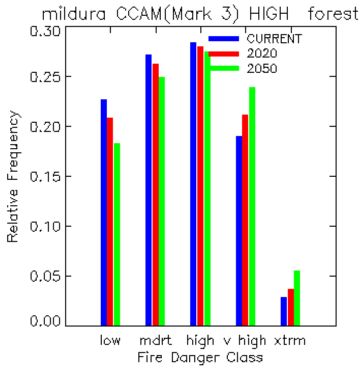
mildura CCAM(Mark 2) LOW forest
CURRENT
2020
2050
Relative Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
low
mdrt
high
v high
xtrm
Fire Danger Class



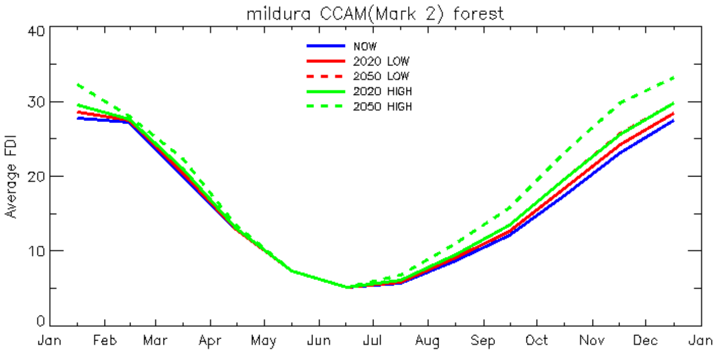
mildura CCAM(Mark 2) HIGH forest
CURRENT
2020
2050
Relative Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
low
mdrt
high
v high
xtrm
Fire Danger Class



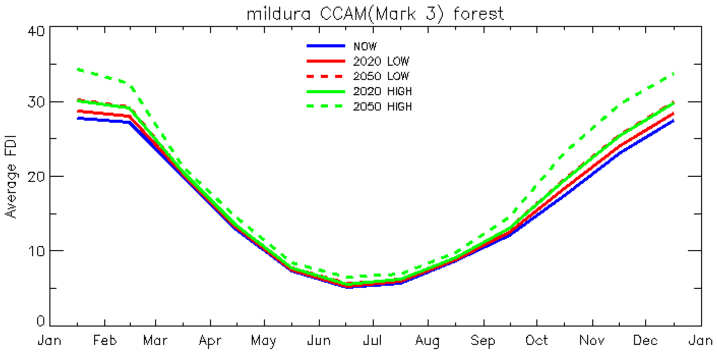
mildura CCAM(Mark 3) LOW forest
CURRENT
2020
2050
Relative Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
low
mdrt
high
v high
xtrm
Fire Danger Class



mildura CCAM(Mark 3) HIGH forest
CURRENT
2020
2050
Relative Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
low
mdrt
high
v high
xtrm
Fire Danger Class

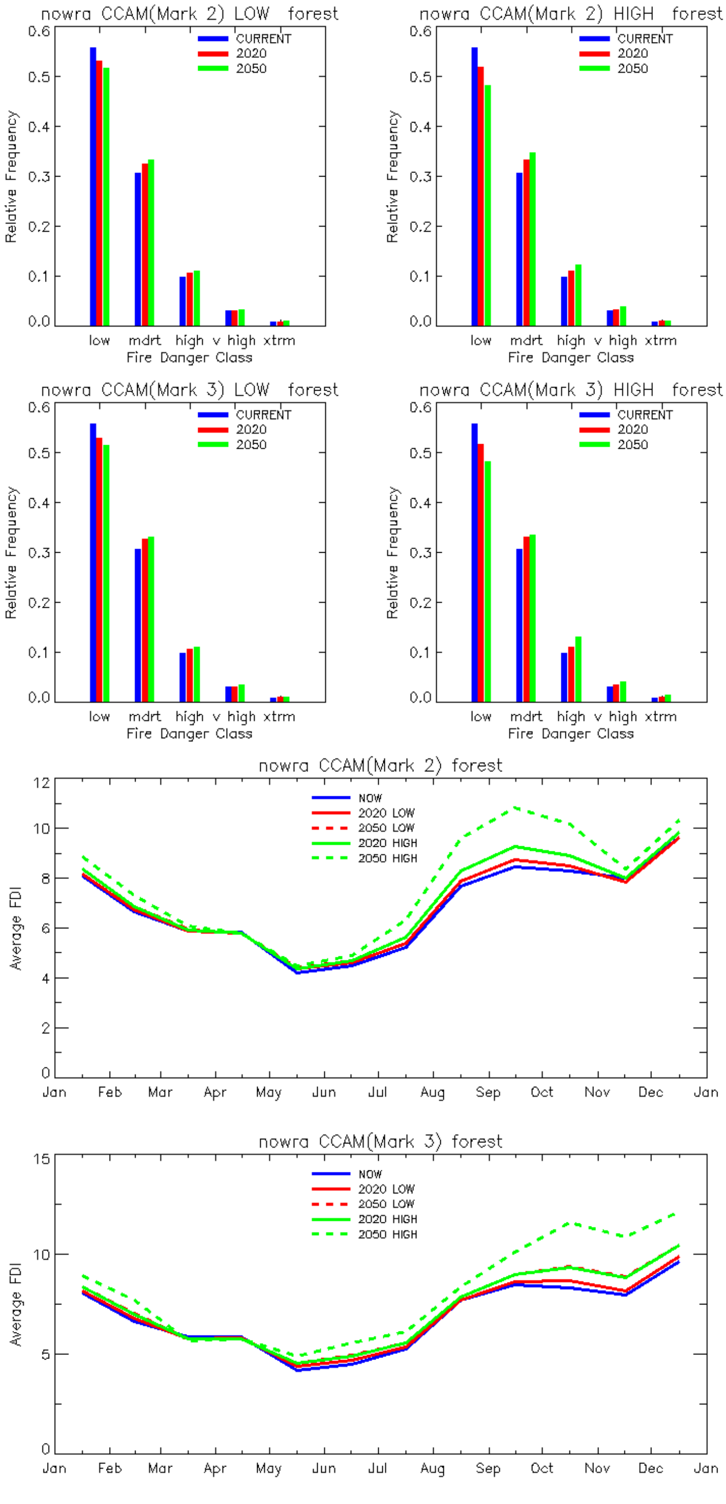


mildura CCAM(Mark 2) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

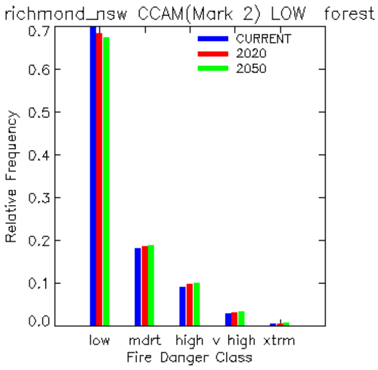


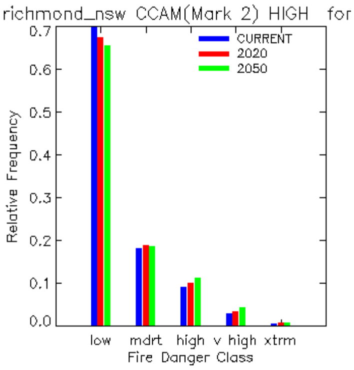
mildura CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

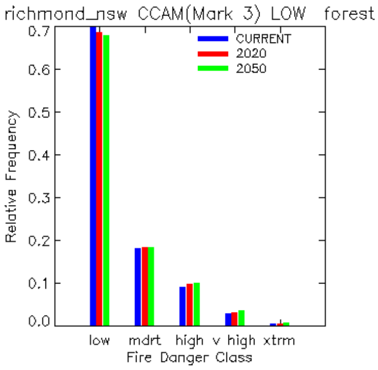
Nowra

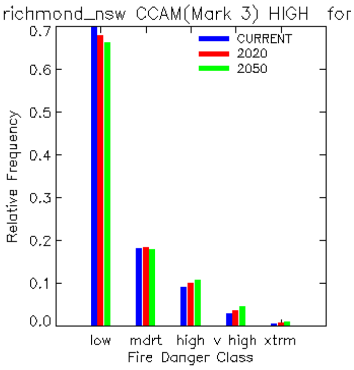

nowra CCAM(Mark 2) LOW forest
nowra CCAM(Mark 2) HIGH forest
nowra CCAM(Mark 3) LOW forest
nowra CCAM(Mark 3) HIGH forest
CURRENT
2020
2050
Relative Frequency
low mdrt high v high xtrm
Fire Danger Class
nowra CCAM(Mark 2) forest
nowra CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

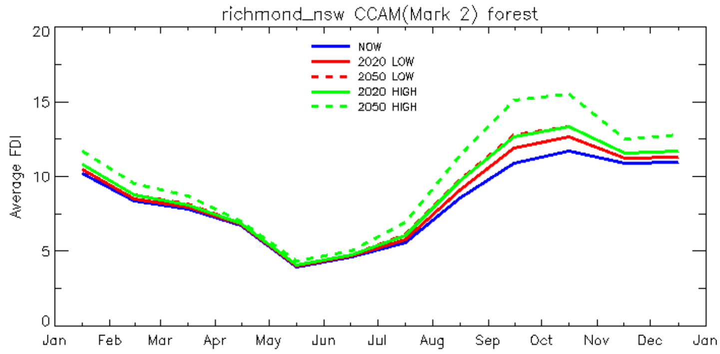
Richmond NSW

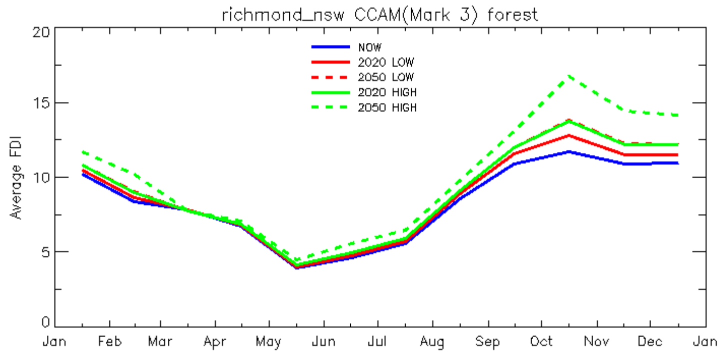




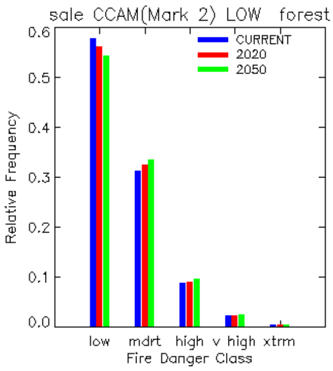


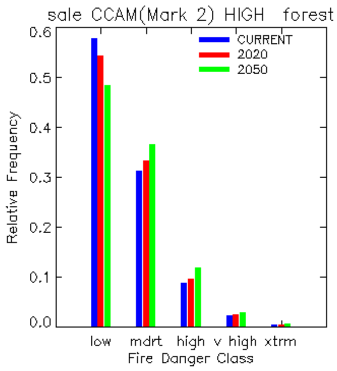


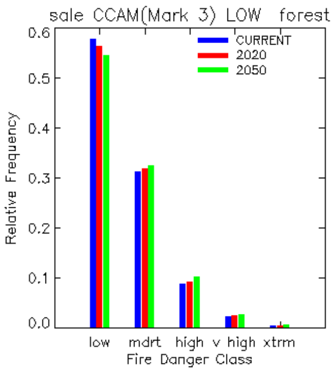


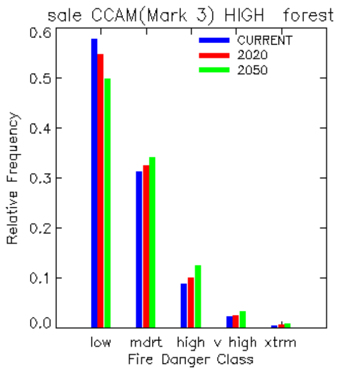


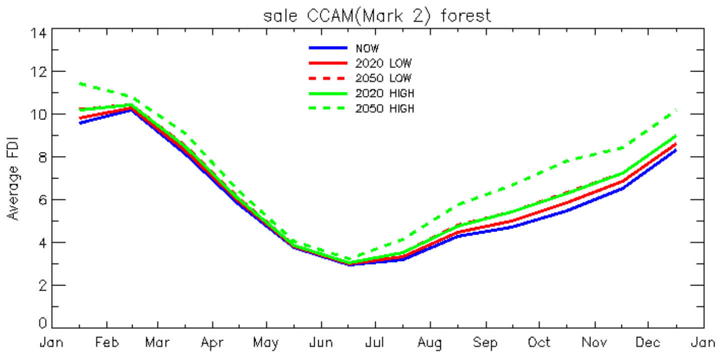
Sale

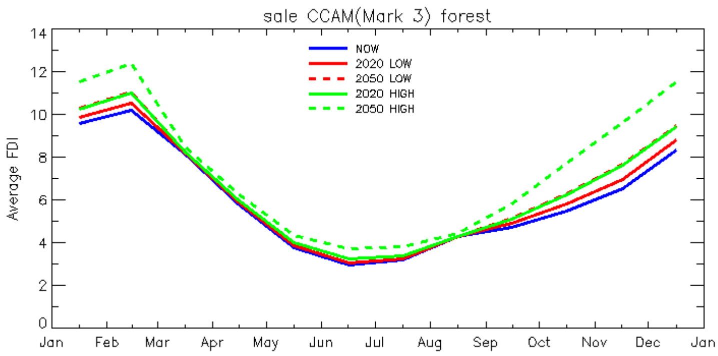

sale CCAM(Mark 2) LOW forest
Relative Frequency
CURRENT
2020
2050
low
mdrt
high
v high
xtrm
Fire Danger Class


sale CCAM(Mark 2) HIGH forest
Relative Frequency
CURRENT
2020
2050
low
mdrt
high
v high
xtrm
Fire Danger Class

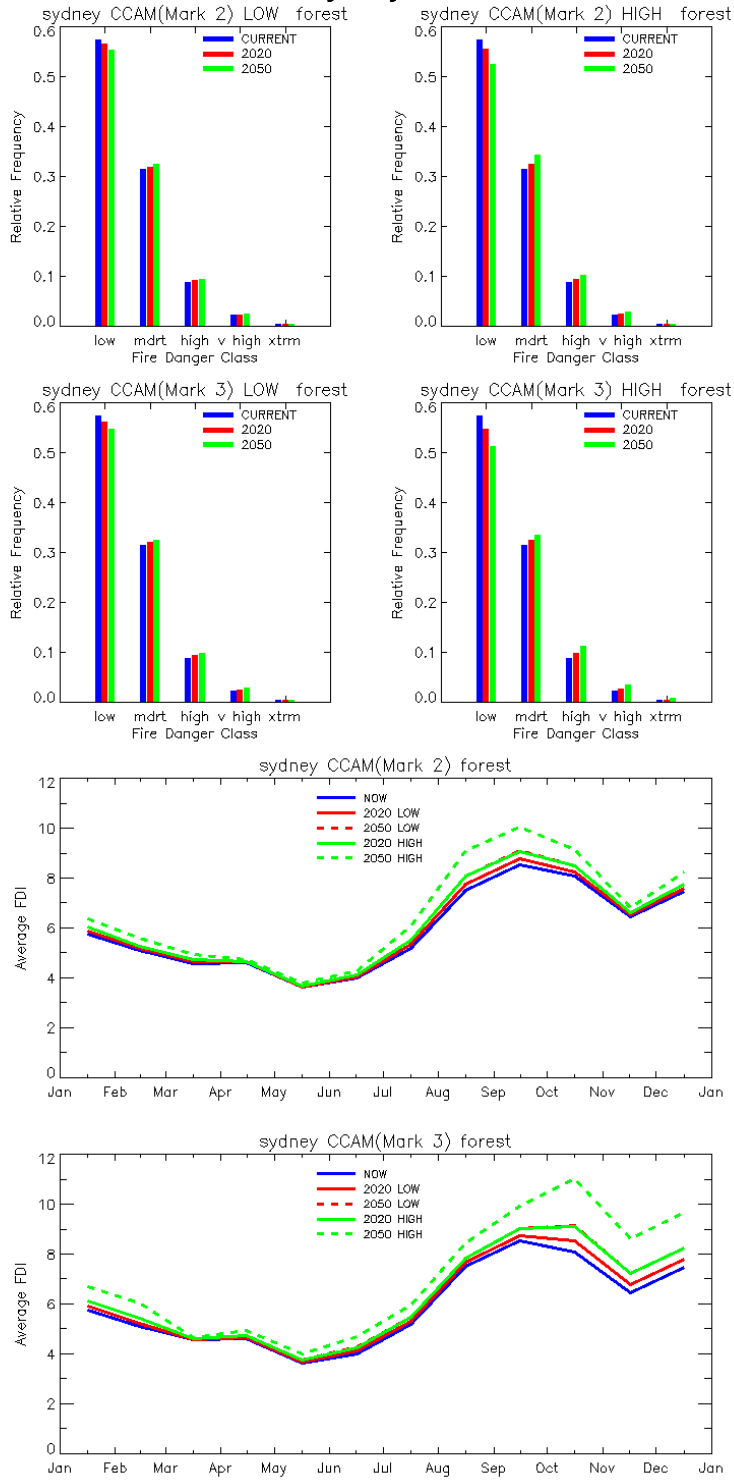

sale CCAM(Mark 3) LOW forest
Relative Frequency
CURRENT
2020
2050
low
mdrt
high
v high
xtrm
Fire Danger Class


sale CCAM(Mark 3) HIGH forest
Relative Frequency
CURRENT
2020
2050
low
mdrt
high
v high
xtrm
Fire Danger Class

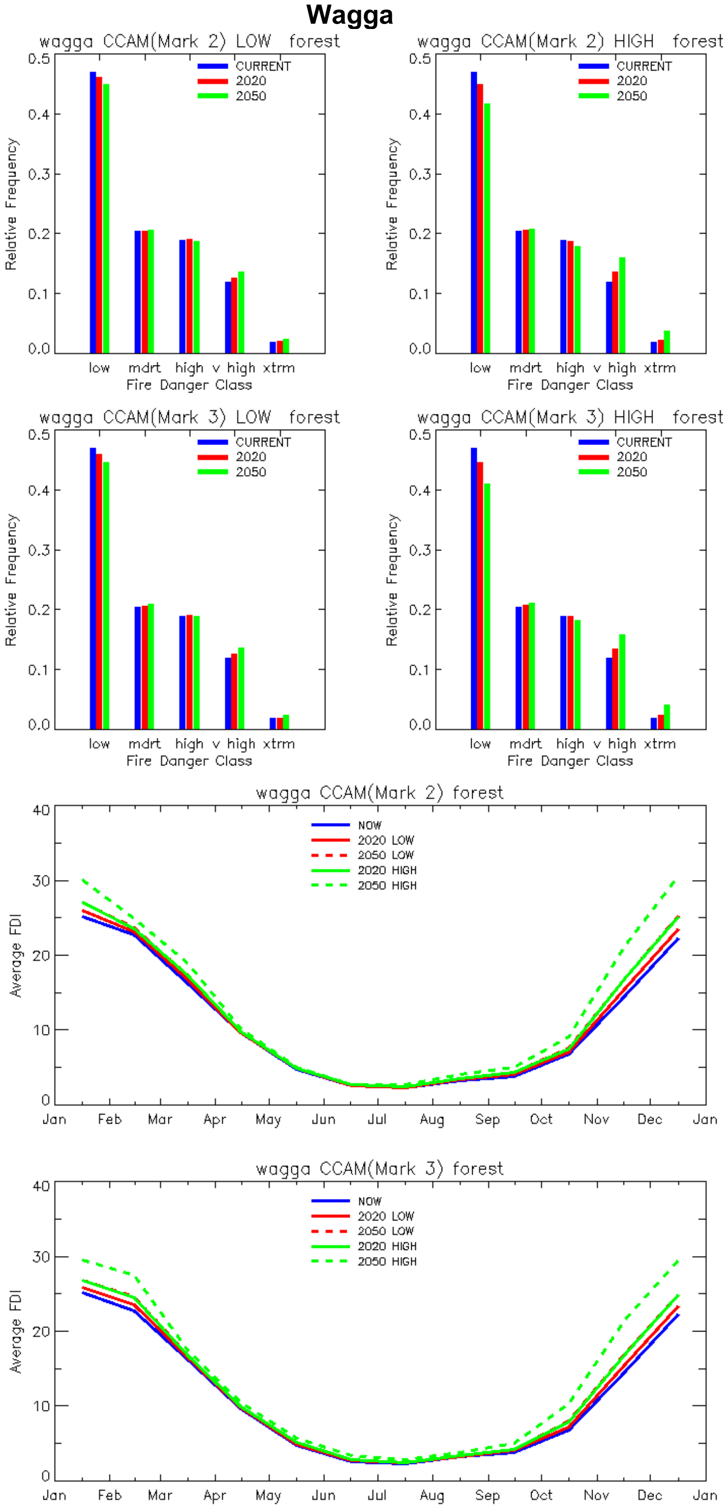

sale CCAM(Mark 2) forest
Average FDI
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan


sale CCAM(Mark 3) forest
Average FDI
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

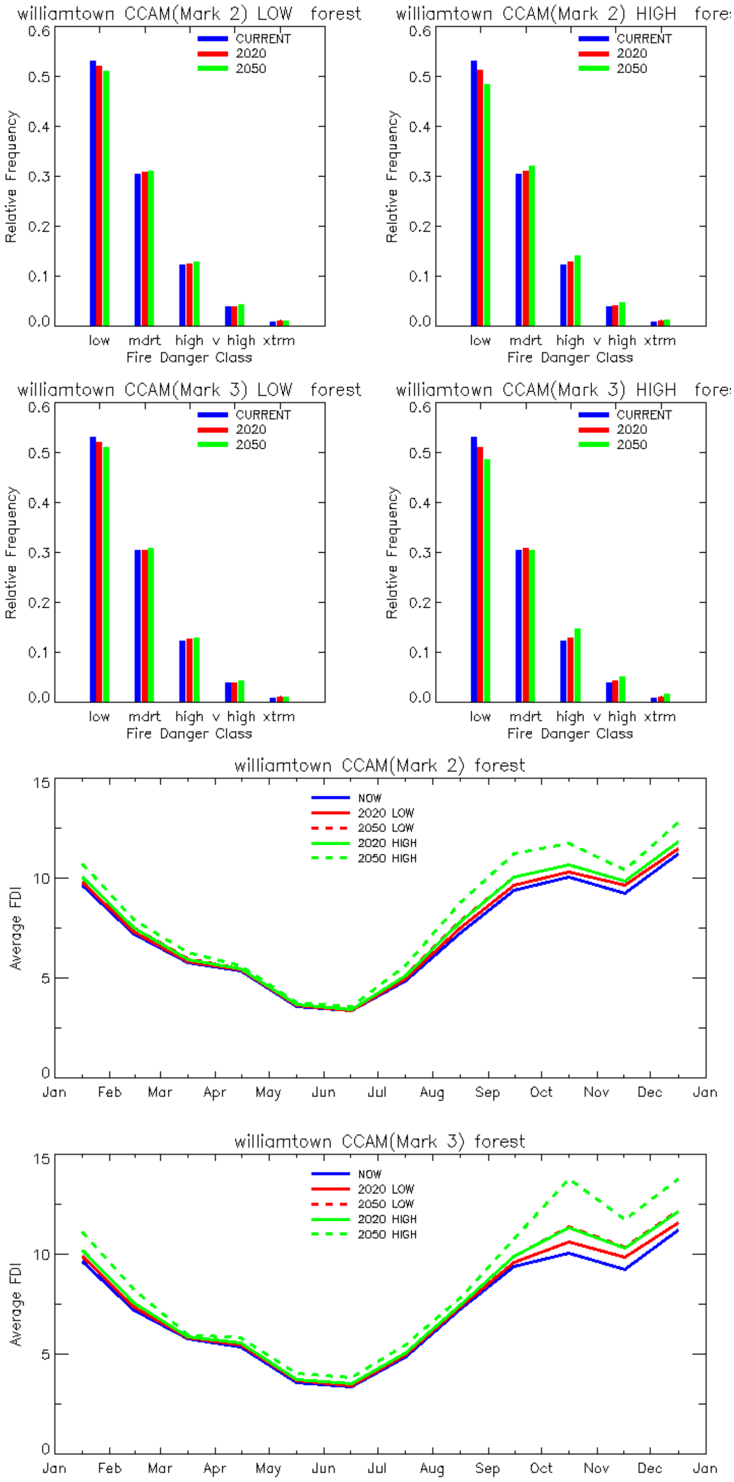
Sydney


sydney CCAM(Mark 2) LOW forest
sydney CCAM(Mark 2) HIGH forest
sydney CCAM(Mark 3) LOW forest
sydney CCAM(Mark 3) HIGH forest
CURRENT
2020
2050
Relative Frequency
low
mdrt
high
v high
xtrm
Fire Danger Class
sydney CCAM(Mark 2) forest
sydney CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Wagga

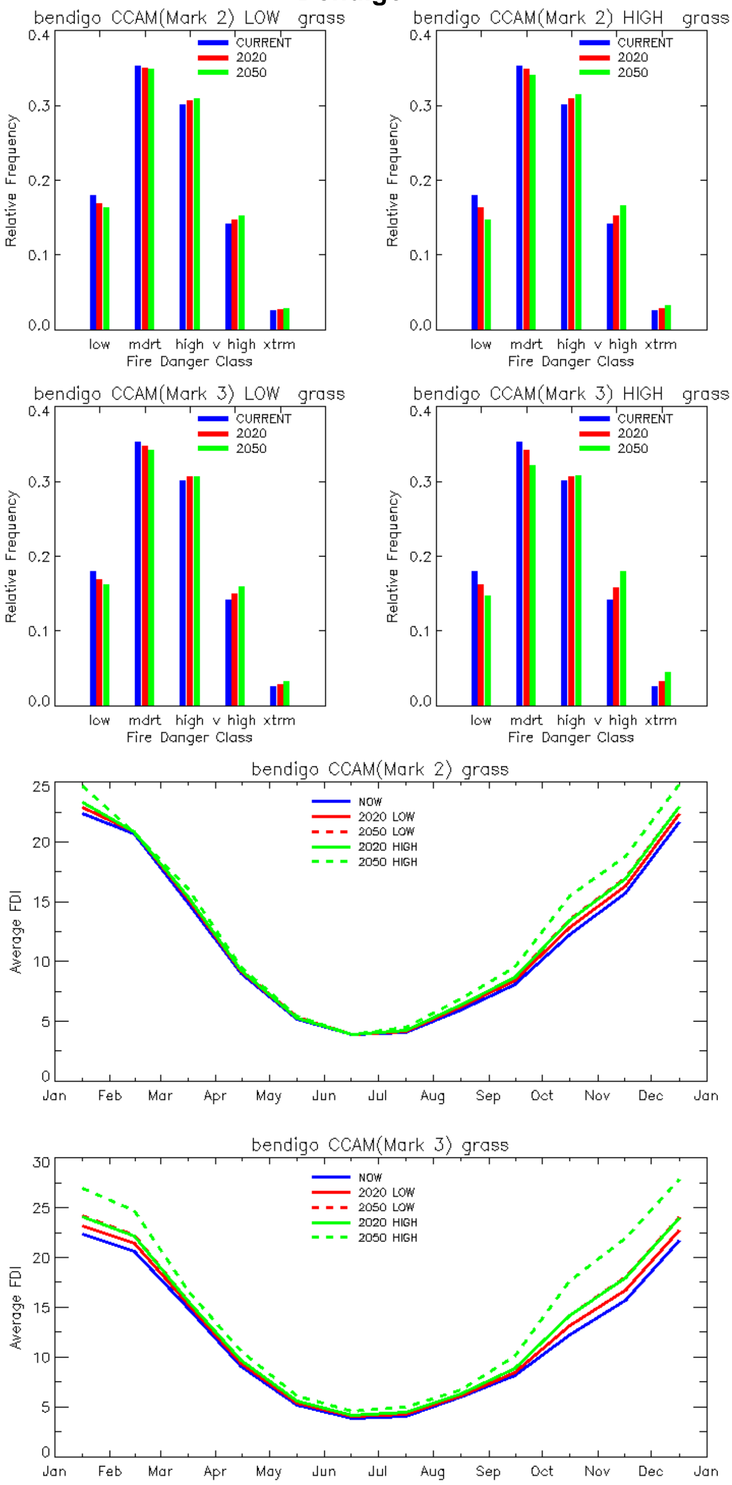

wagga CCAM(Mark 2) LOW forest
wagga CCAM(Mark 2) HIGH forest
wagga CCAM(Mark 3) LOW forest
wagga CCAM(Mark 3) HIGH forest
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
low
mdrt
high
v high
xtrm
Fire Danger Class
wagga CCAM(Mark 2) forest
wagga CCAM(Mark 3) forest
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

Williamtown

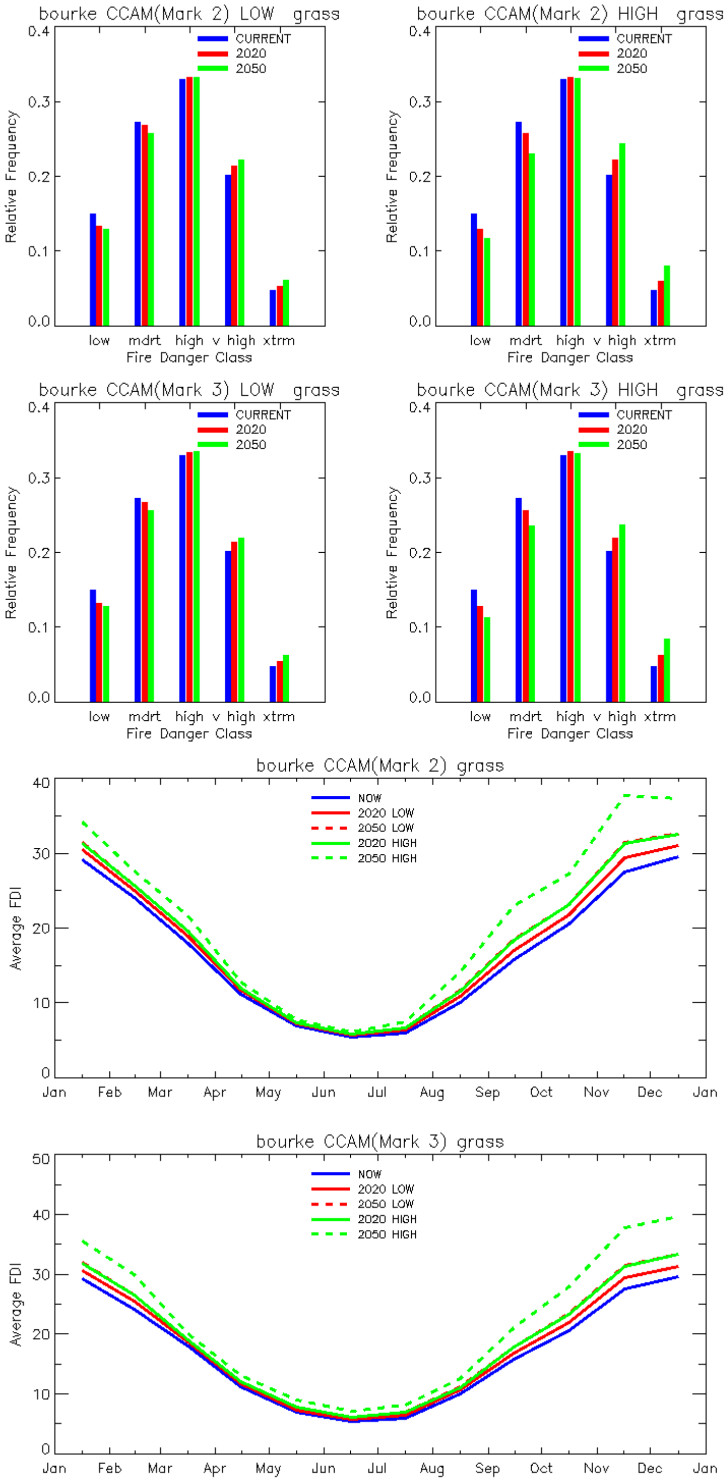


Appendix 5: Grassland Fire Danger Index

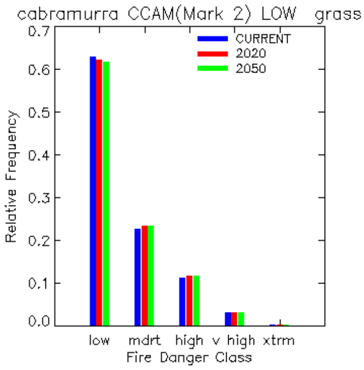
Bendigo

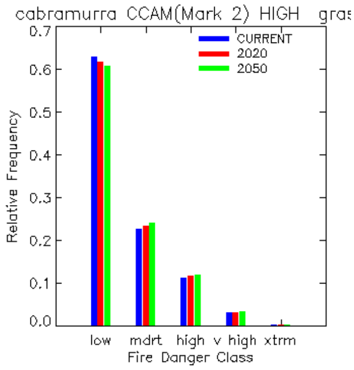


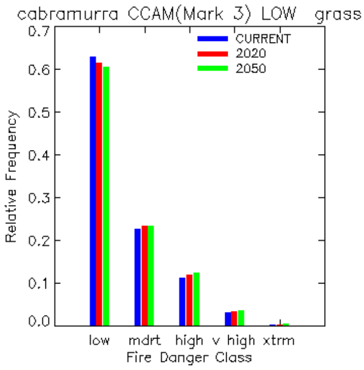
Bourke

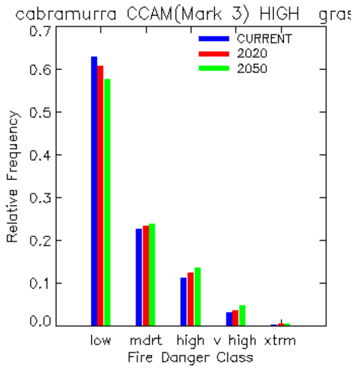

bourke CCAM(Mark 2) LOW grass
bourke CCAM(Mark 2) HIGH grass
bourke CCAM(Mark 3) LOW grass
bourke CCAM(Mark 3) HIGH grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
low
mdrt
high
v high
xtrm
Fire Danger Class
bourke CCAM(Mark 2) grass
bourke CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
30
40
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

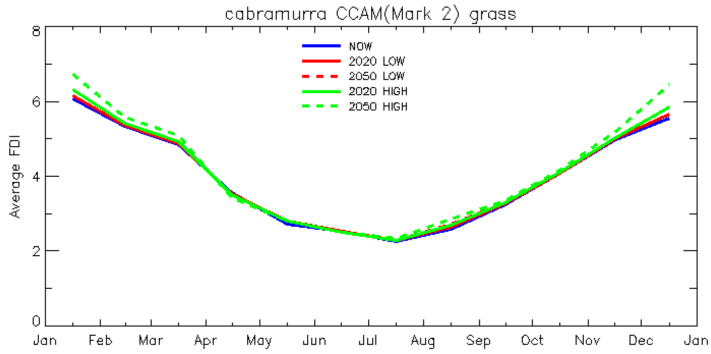
Cabramurra

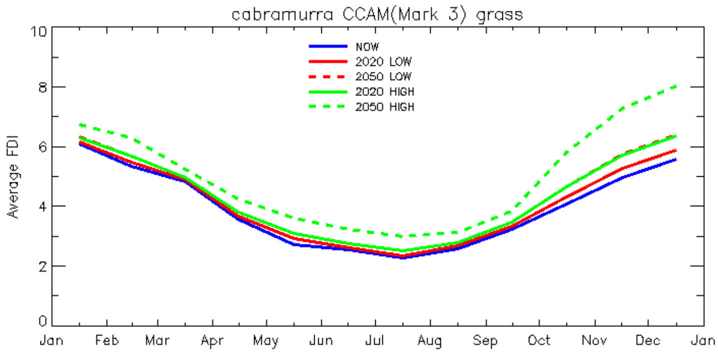

cabramurra CCAM(Mark 2) LOW grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
low
mdrt
high
v high
xtrm
Fire Danger Class


cabramurra CCAM(Mark 2) HIGH gras
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
low
mdrt
high
v high
xtrm
Fire Danger Class

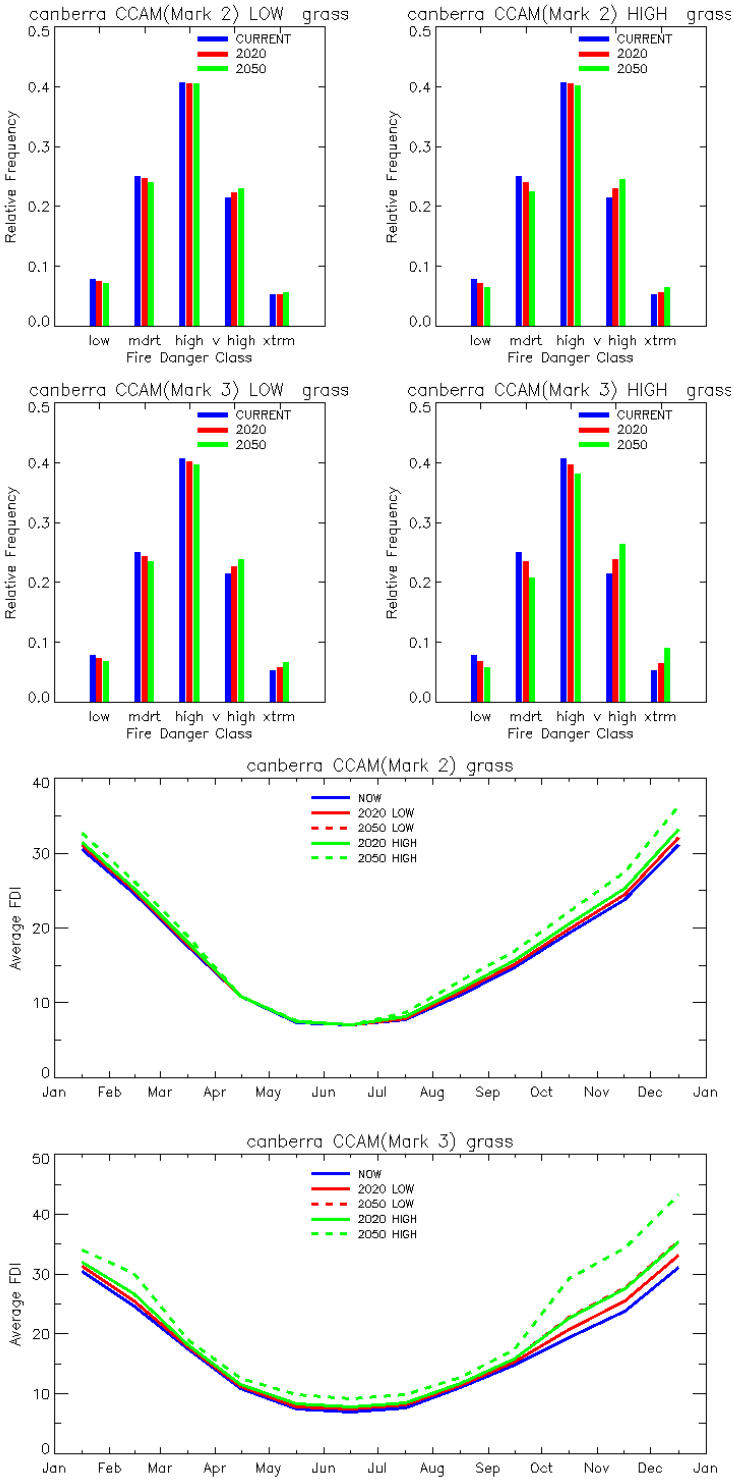

cabramurra CCAM(Mark 3) LOW grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
low
mdrt
high
v high
xtrm
Fire Danger Class


cabramurra CCAM(Mark 3) HIGH gras
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
low
mdrt
high
v high
xtrm
Fire Danger Class

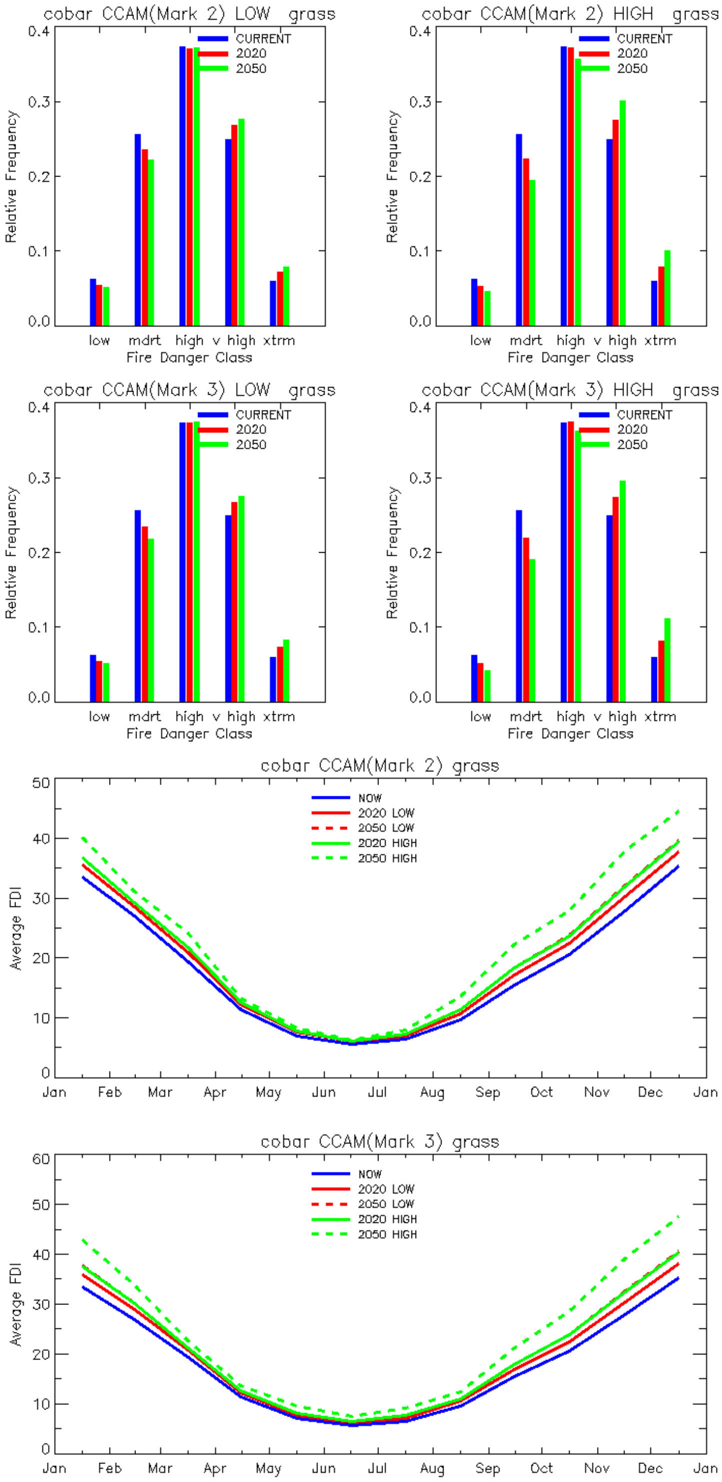

cabramurra CCAM(Mark 2) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
2
4
6
8
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan


cabramurra CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
2
4
6
8
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

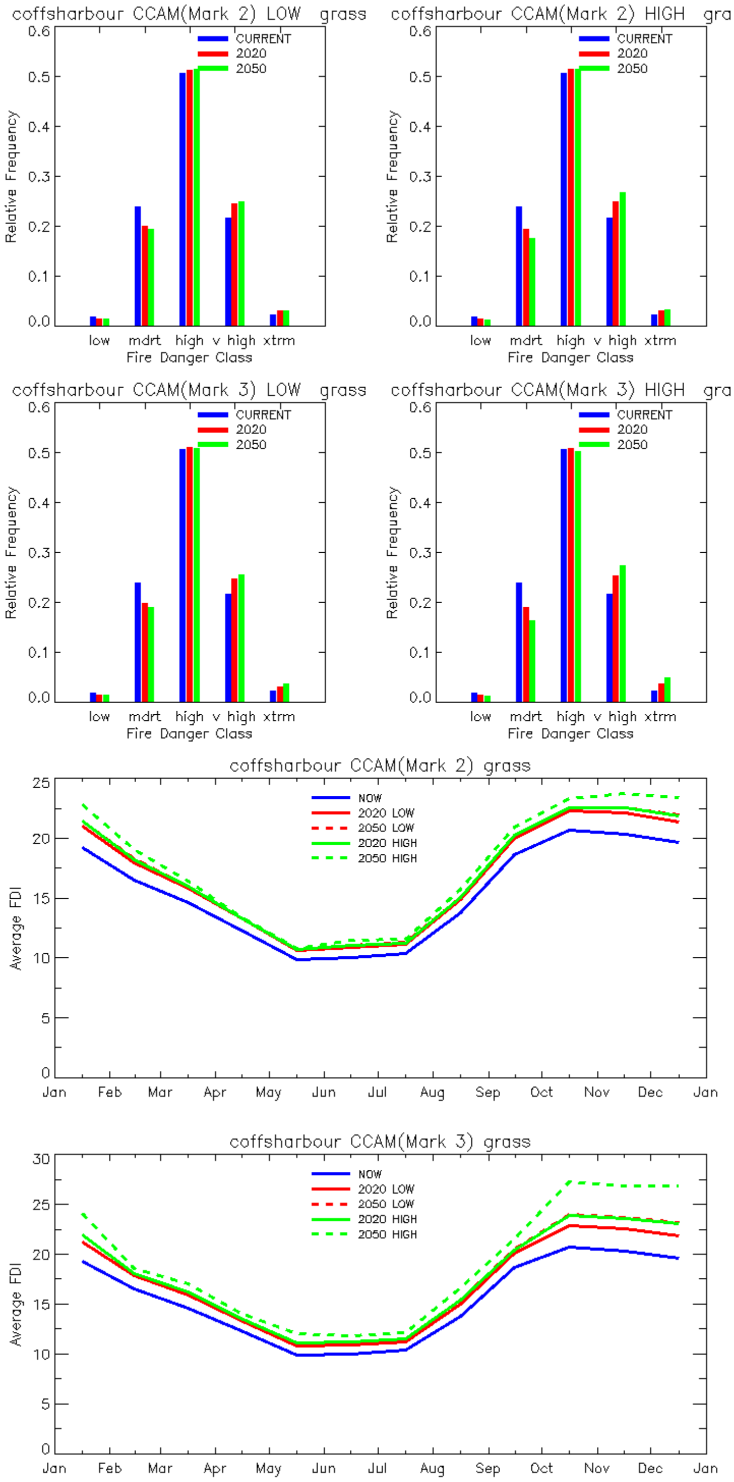
Canberra


canberra CCAM(Mark 2) LOW grass
canberra CCAM(Mark 2) HIGH grass
canberra CCAM(Mark 3) LOW grass
canberra CCAM(Mark 3) HIGH grass
CURRENT
2020
2050
Relative Frequency
low
mdrt
high
v high
xtrm
Fire Danger Class
canberra CCAM(Mark 2) grass
canberra CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

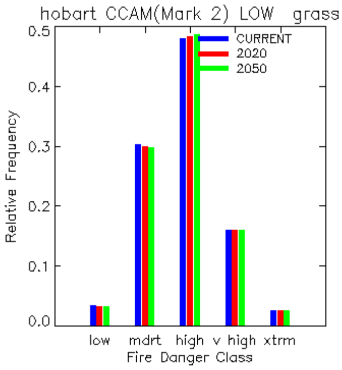
Cobar

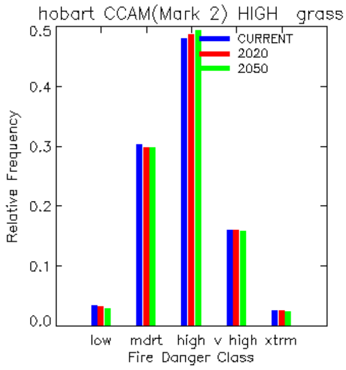

cobar CCAM(Mark 2) LOW grass
cobar CCAM(Mark 2) HIGH grass
cobar CCAM(Mark 3) LOW grass
cobar CCAM(Mark 3) HIGH grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
low
mdrt
high
v high
xtrm
Fire Danger Class
cobar CCAM(Mark 2) grass
cobar CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
30
40
50
60
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

Coffs Harbour



Hobart


hobart CCAM(Mark 2) LOW grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
low
mdrt
high
v high
xtrm
Fire Danger Class


hobart CCAM(Mark 2) HIGH grass
CURRENT
2020
2050
Relative Frequency
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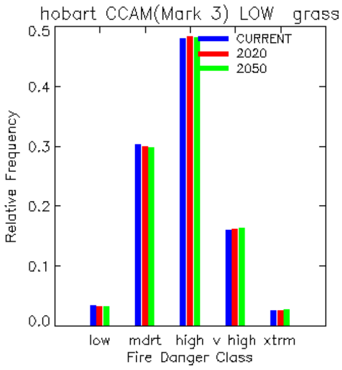
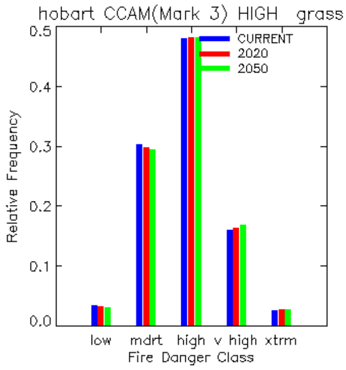
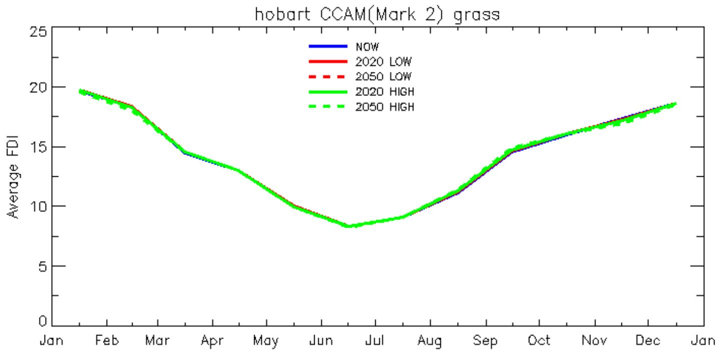
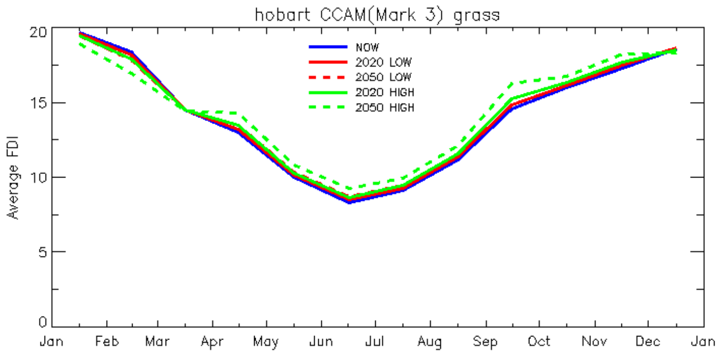
0.1
0.2
0.3
0.4
0.5
low
mdrt
high
v high
xtrm
Fire Danger Class


hobart CCAM(Mark 3) LOW grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
low
mdrt
high
v high
xtrm
Fire Danger Class


hobart CCAM(Mark 3) HIGH grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
low
mdrt
high
v high
xtrm
Fire Danger Class


hobart CCAM(Mark 2) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
5
10
15
20
25
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan


hobart CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
5
10
15
20
Jan
Feb
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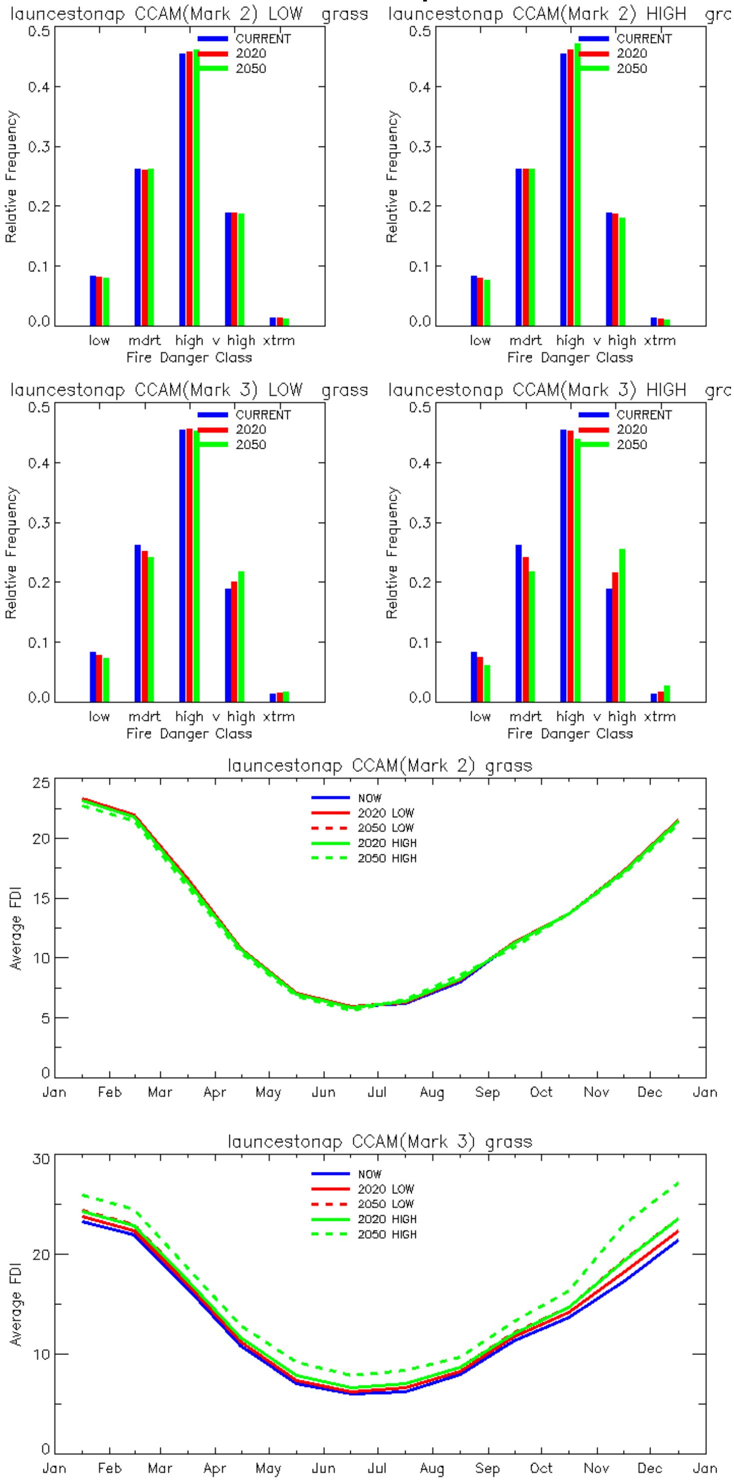
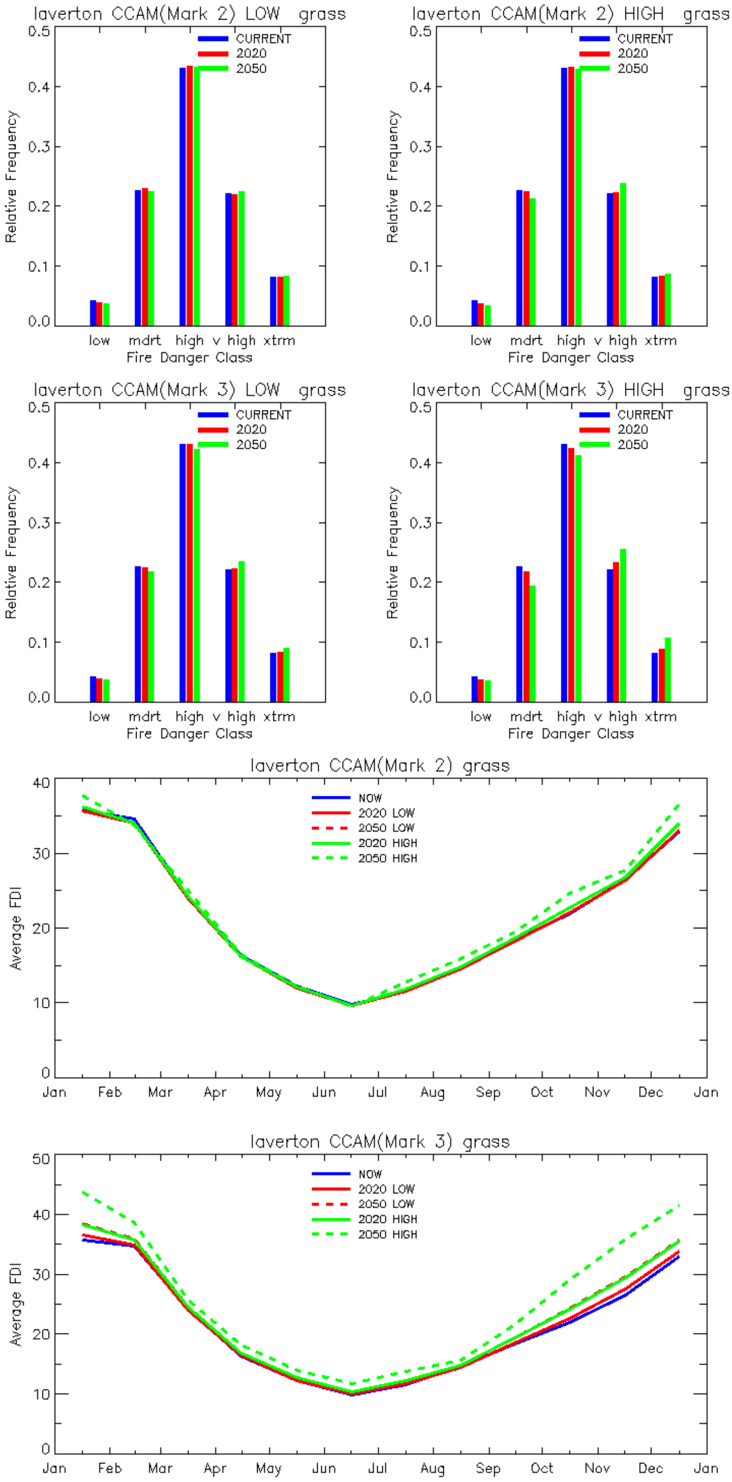
Sep
Oct
Nov
Dec
Jan

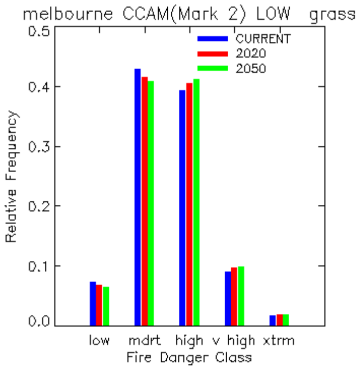
Launceston Airport



Laverton


laverton CCAM(Mark 2) LOW grass
laverton CCAM(Mark 2) HIGH grass
laverton CCAM(Mark 3) LOW grass
laverton CCAM(Mark 3) HIGH grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
low mdrt high v high xtrm
Fire Danger Class
laverton CCAM(Mark 2) grass
laverton CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
30
40
50
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

Melbourne



melbourne CCAM(Mark 2) LOW grass
CURRENT
2020
2050
Relative Frequency
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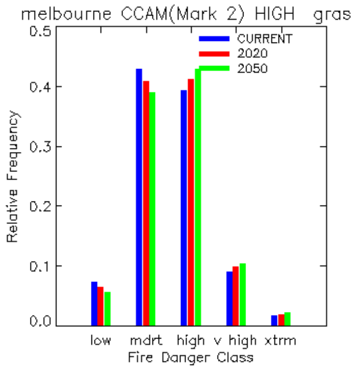
0.1
0.2
0.3
0.4
0.5
low
mdrt
high
v high
xtrm
Fire Danger Class



melbourne CCAM(Mark 2) HIGH gras
CURRENT
2020
2050
Relative Frequency
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0.4
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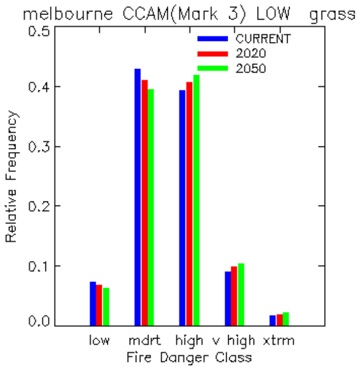
low
mdrt
high
v high
xtrm
Fire Danger Class



melbourne CCAM(Mark 3) LOW grass
CURRENT
2020
2050
Relative Frequency
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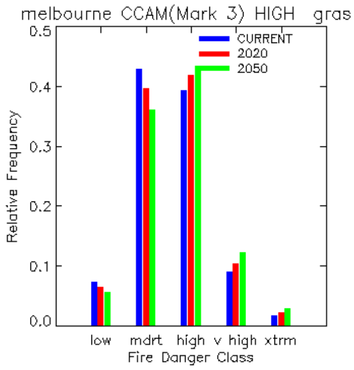
0.1
0.2
0.3
0.4
0.5
low
mdrt
high
v high
xtrm
Fire Danger Class



melbourne CCAM(Mark 3) HIGH gras
CURRENT
2020
2050
Relative Frequency
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0.3
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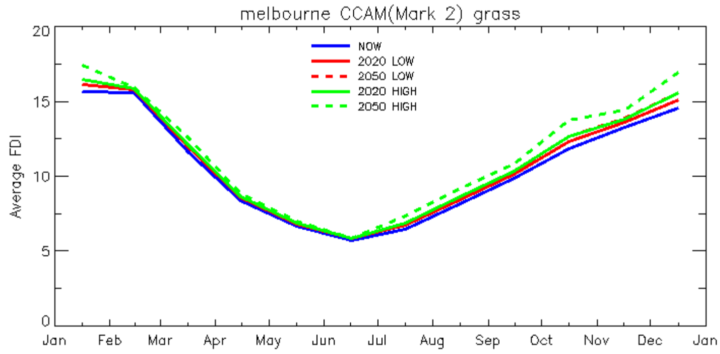
low
mdrt
high
v high
xtrm
Fire Danger Class



melbourne CCAM(Mark 2) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
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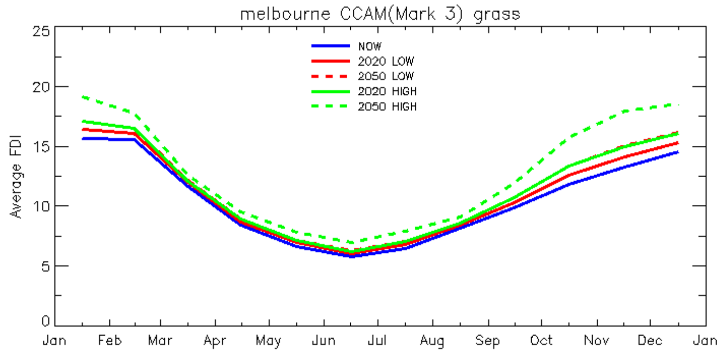
Nov
Dec
Jan



melbourne CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
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25
Jan
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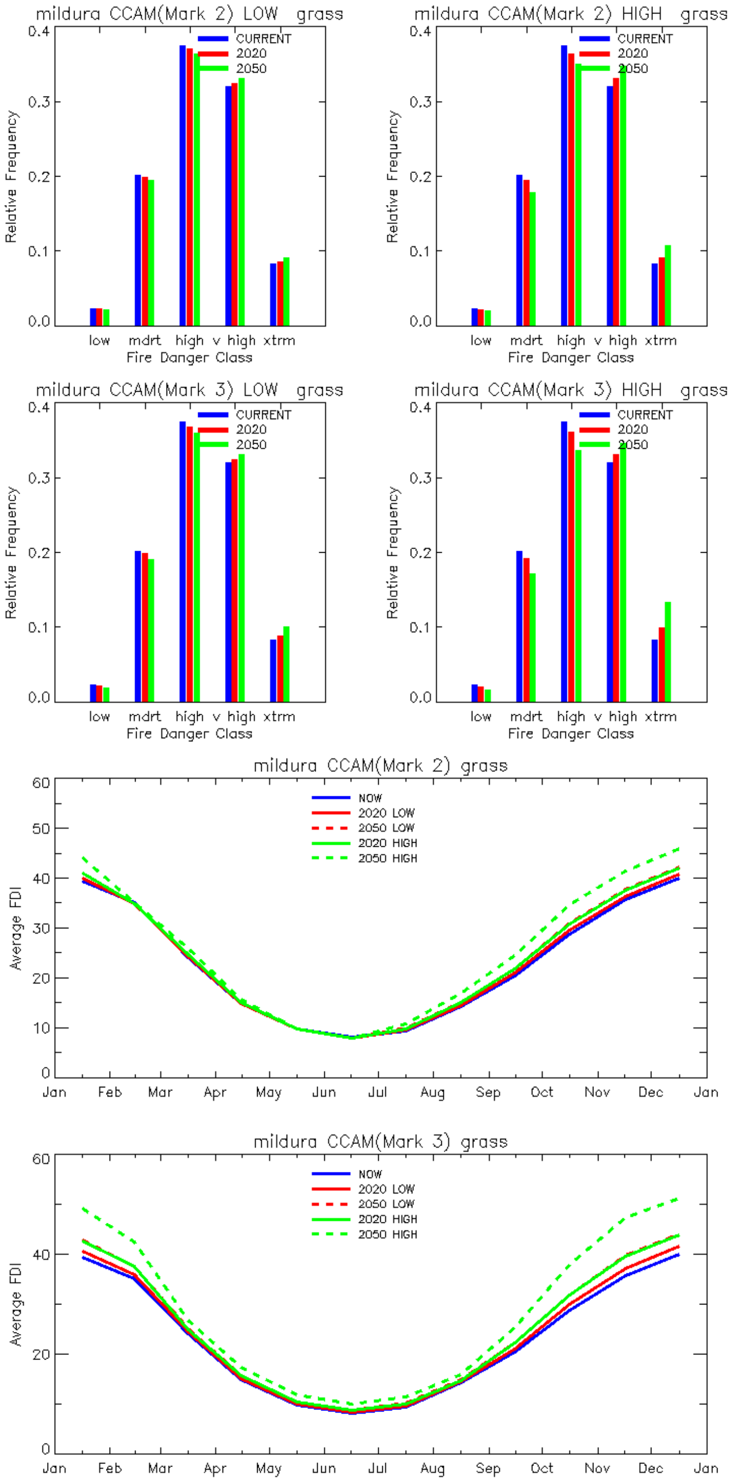
Jan

Mildura


mildura CCAM(Mark 2) LOW grass
mildura CCAM(Mark 2) HIGH grass
mildura CCAM(Mark 3) LOW grass
mildura CCAM(Mark 3) HIGH grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
low
mdrt
high
v high
xtrm
Fire Danger Class
mildura CCAM(Mark 2) grass
mildura CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
10
20
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50
60
Jan
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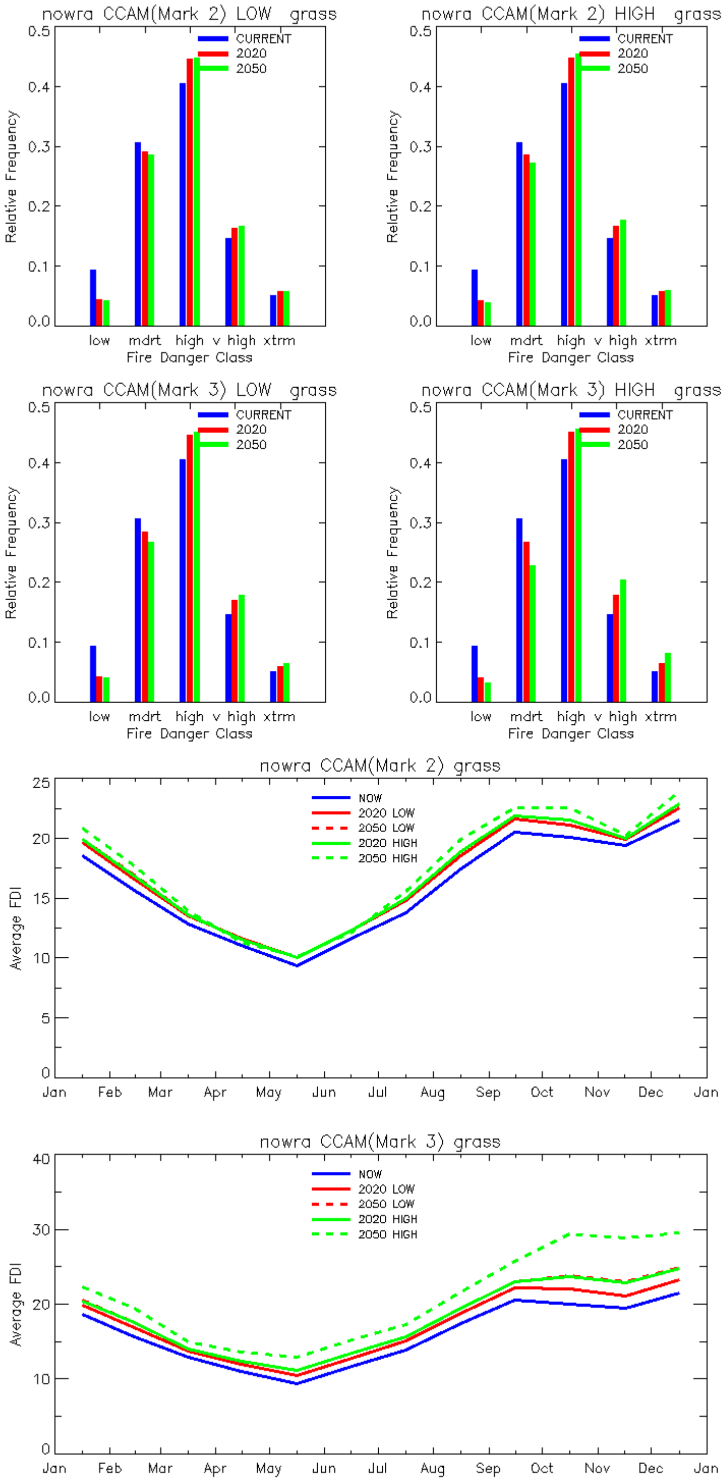
Nov
Dec
Jan

Nowra


nowra CCAM(Mark 2) LOW grass
nowra CCAM(Mark 2) HIGH grass
nowra CCAM(Mark 3) LOW grass
nowra CCAM(Mark 3) HIGH grass
CURRENT
2020
2050
Relative Frequency
0.0
0.1
0.2
0.3
0.4
0.5
low
mdrt
high
v high
xtrm
Fire Danger Class
nowra CCAM(Mark 2) grass
nowra CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
Jan
Feb
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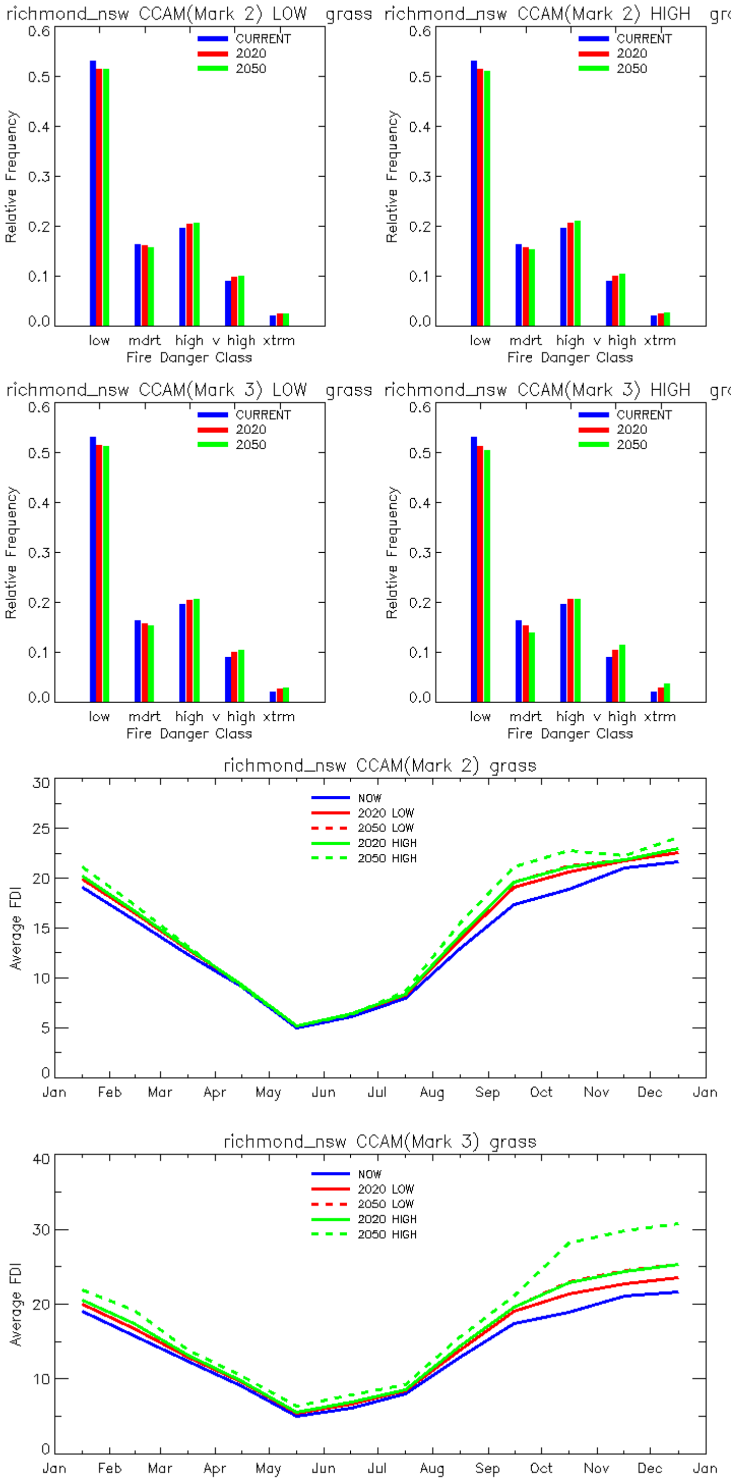
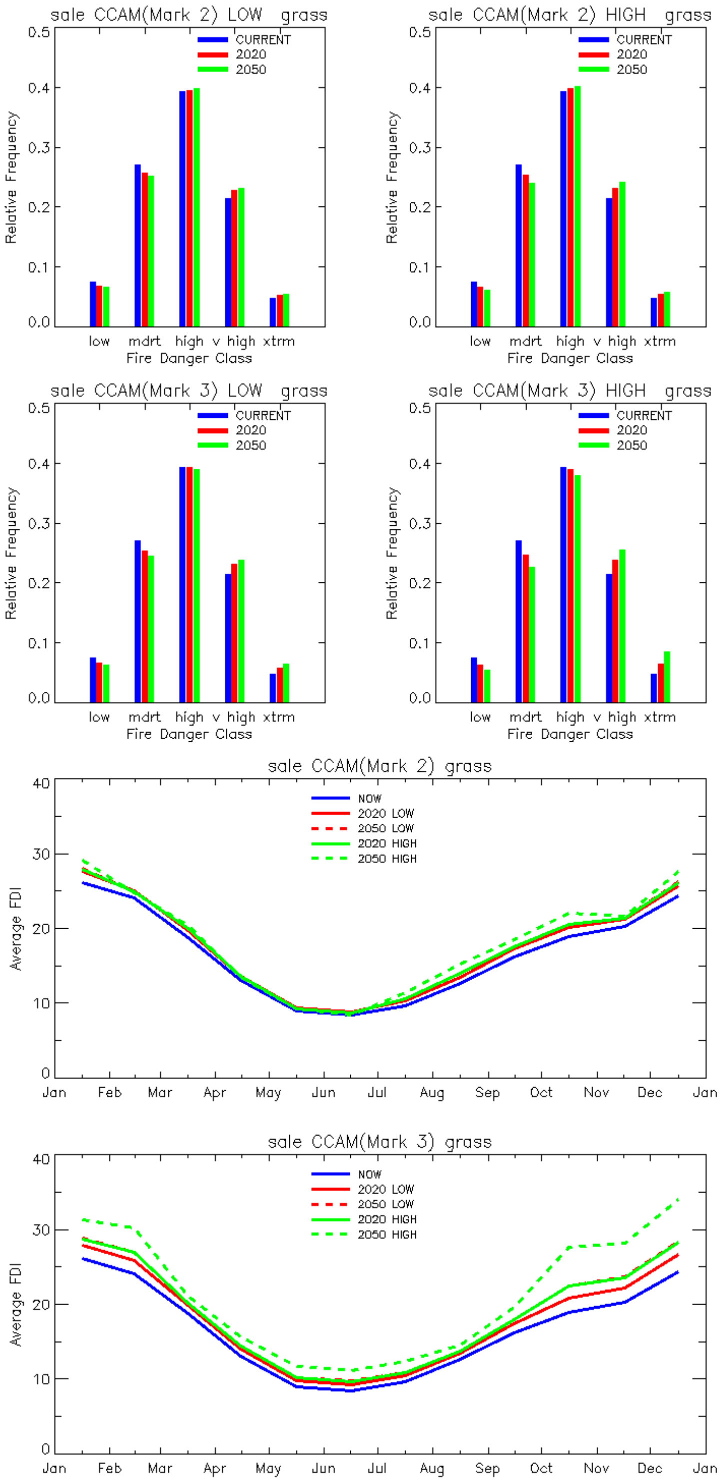
Sep
Oct
Nov
Dec
Jan

Richmond NSW

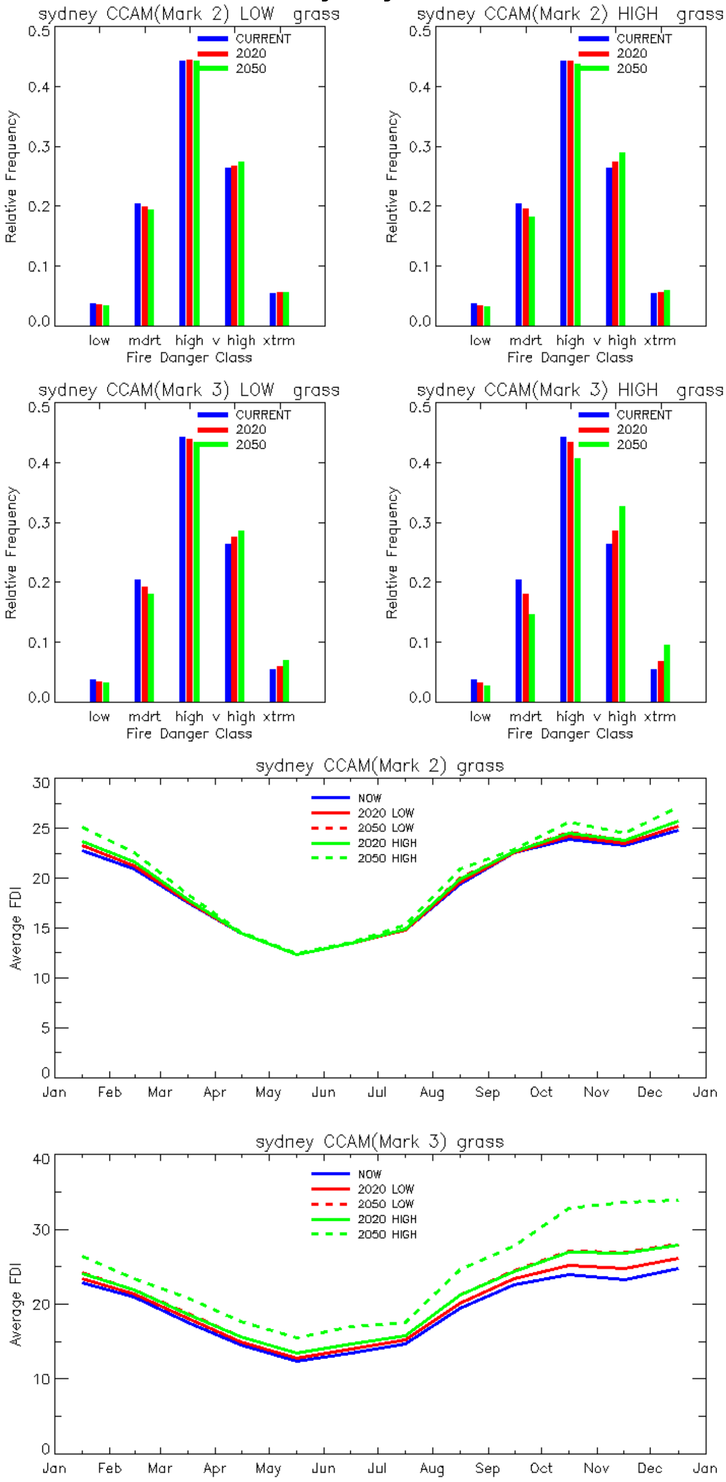


Sale

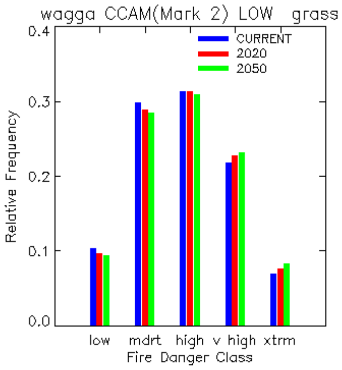


sale CCAM(Mark 2) LOW grass
sale CCAM(Mark 2) HIGH grass
sale CCAM(Mark 3) LOW grass
sale CCAM(Mark 3) HIGH grass
CURRENT
2020
2050
Relative Frequency
low mdrt high v high xtrm
Fire Danger Class
sale CCAM(Mark 2) grass
sale CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

Sydney


sydney CCAM(Mark 2) LOW grass
sydney CCAM(Mark 2) HIGH grass
sydney CCAM(Mark 3) LOW grass
sydney CCAM(Mark 3) HIGH grass
CURRENT
2020
2050
Relative Frequency
low mdrt high v high xtrm
Fire Danger Class
sydney CCAM(Mark 2) grass
sydney CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

Wagga


wagga CCAM(Mark 2) LOW grass
CURRENT
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2050
Relative Frequency
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0.1
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0.4
low
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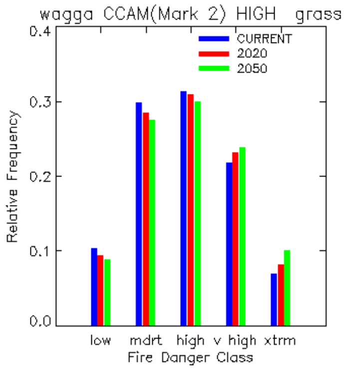
high
v high
xtrm
Fire Danger Class


wagga CCAM(Mark 2) HIGH grass
CURRENT
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2050
Relative Frequency
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0.2
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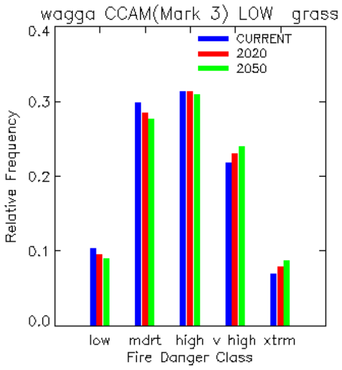
0.4
low
mdrt
high
v high
xtrm
Fire Danger Class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CURRENT
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Relative Frequency
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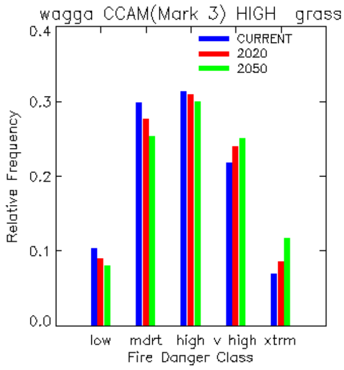
low
mdrt
high
v high
xtrm
Fire Danger Class


wagga CCAM(Mark 3) HIGH grass
CURRENT
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Relative Frequency
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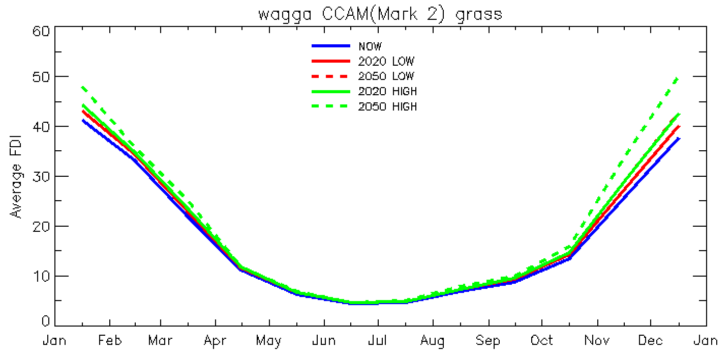
v high
xtrm
Fire Danger Class


wagga CCAM(Mark 2) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
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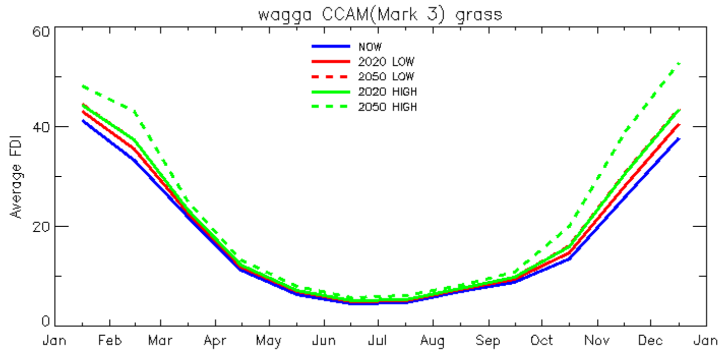
wagga CCAM(Mark 3) grass
NOW
2020 LOW
2050 LOW
2020 HIGH
2050 HIGH
Average FDI
0
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60
Jan
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Dec
Jan

Williamtown