National Bushfire Mitigation – Tasmanian Grants Program (NBMP)

An assessment of the viability of prescribed burning as a management tool under a changing climate

ANTARCTIC CLIMATE & ECOSYSTEMS COOPERATIVE RESEARCH CENTRE

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The ACE CRC is a unique collaboration between the Australian Antarctic Division, the Bureau of Meteorology, CSIRO, the University of Tasmania, the Australian Government's Department of the Environment, the Alfred Wegener Institute for Polar and Marine Research (Germany), and the National Institute of Water and Atmospheric Research Ltd (New Zealand) and a consortium of supporting partners. It is funded by the Australian Government's Cooperative Research Centres Programme.

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DEFINITION OF TERMS AND ABBREVIATIONS USED IN THIS REPORT

CCAM

The Conformal Cubic Atmospheric Model (CCAM) is the regional climate model used to generate the Climate Futures for Tasmania projections. It was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Climate projections

A climate projection is a model-derived description of possible future climates under a given set of plausible scenarios of climate forcings (any influence on the climate that originates from outside the climate system itself). Climate projections differ from climate predictions because they depend on the greenhouse gas emission/concentration/radiative forcing scenario used. Such scenarios are based on assumptions about future socio–economic and technological developments that are subject to substantial uncertainty. A projection is therefore a probabilistic statement of what could happen if certain assumed conditions prevail in the future.

CMIP3 archive

The Coupled Model Intercomparison Project phase 3 archive. The CMIP3 archive includes a standard set of model simulations that have been assessed as providing plausible projections of future climate change. Models admitted to the CMIP3 archive informed the IPCC's Fourth Assessment Report.

Emissions scenario (A2)

Reported in this study is the SRES high emissions scenario (A2) used in the Fourth Assessment Report (AR4). This scenario does not include any mitigation target, resulting in considerable increases in greenhouse gas emissions and concentrations over time. A2 projects increases in global mean temperatures of 2.0–5.4°C for 2090-2099 (relative to 1980-1999). Over the past decade, global emissions have tracked the higher end of the A2 pathway.

In the Fifth Assessment Report (AR5), the Special Report on Emissions Scenarios (SRES) were replaced by Representative Concentration Pathways (RCPs). The four RCPs (2.6, 4.5, 6, and 8.5 W/m2) represent alternative greenhouse gas concentration trajectories resulting from different climate policies. SRES A2 projects a similar acceleration in temperature to RCP8.5, although median temperatures are consistently higher in the RCP8.5.

Host models

The Global Climate Models used in this study were ECHAM5/MPI-OM, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2(medres), UKMO-HadCM3 and CSIRO-Mk3.5. The range in projected changes across the six models is presented in Part II to indicate a range of plausible futures under climate change.

Baseline and Future time periods

In this report the projected changes in climate are calculated between the means of the baseline period (1961-1990) and two future time periods (mid-century (2041-2070) and end of century (2071-2100). 30-year periods are used to incorporate the yearly and decadal variability that is natural in the climate system, for example, during droughts or cool seasons.

Multi-model mean

Some results are presented in this report as the average of six climate models. This approach is commonly used in climatology to provide a 'central estimate' of the projections. Since all climate models admitted to the CMIP3 archive are considered to represent plausible representations of possible futures, several models are used to incorporate the uncertainty due to the range in climate models.

Executive Summary

Fire danger is projected to increase across much of Tasmania under ongoing climate change, with the fire season starting earlier in the year, and lasting for longer. Prescribed burning is currently the only effective method of managing bushfire risk at the landscape scale in Tasmania and is generally carried out during autumn (and to a lesser extent spring), when weather conditions allow low intensity burns to be safely managed.

Objectives of the report

This report investigates the changing conditions for prescribed burning in Tasmania under climate change, with a focus on three aspects:

1. seasonal and monthly changes in the climate variables that determine when prescribed burning can be applied (rainfall, temperature, fuel moisture and atmospheric stability);
2. the frequency and distribution of daily weather patterns associated with atmospheric instability and extreme fire danger;
3. changes to broad vegetation types that may result from the interaction between climate change and frequency of burning.

Report findings

<u>Changes in climate variables between current and future time periods</u>

The results show that, by the end of century, under the high emissions scenario (RCP 8.5) considered here:

1. Temperatures across Tasmania may increase by up to 2.7°C;
2. Increases in maximum temperatures in each month represent a shift of at least one month towards temperatures currently experienced in warmer months;
3. Days exceeding the 25°C threshold above which the operational guidelines restrict prescribed burning are projected to occur regularly in November, while they currently only occur regularly in December, January and February;
4. Rainfall changes are variable across Tasmania. Reduced rainfall in spring is projected for the Central Plateau, East Coast, King Island, North West and Midlands districts. Increased rainfall in September and October is projected for the Furneaux and Western districts. Substantial reductions in autumn rainfall are projected for the Western district;

5. Substantial increases in fuel availability (indicated by the Drought Factor) and decreases in fuel moisture (Soil Dryness Index, SDI) are projected. These trends become evident in the near future (2021-2040), with very strong drying trends emerging for autumn and spring by the end of the century;
6. Increases in SDI are greatest in the summer and autumn months by the end of the century (2081-2100). Smaller increases are projected in late winter and spring months. Increases in the SDI values for both June and November are so substantial that the wettest period (for SDI) is projected to be 2 months shorter by the end of century.
7. Periods of higher flammability will be brought forward earlier in the season, and extend later;
8. As the frequency of warmer and drier conditions increases in autumn and spring, the likelihood of all variables coinciding at their maximum values (e.g. maximum wind speed, lowest relative humidity, highest Soil Dryness Index and Drought Factor) can be expected to increase. This increases the likelihood that fires will burn with faster rates of spread, higher intensities and a higher risk of escape than under current conditions.
9. Conditions conducive to safe, low intensity burning will occur less frequently in spring and autumn;
10. Flammability of vegetation will increase in these seasons, reducing the ability to safely conduct and contain prescribed burns.

<u>Changes to weather conditions suitable for prescribed burning</u>

The analyses show:

1. The patterns of synoptic weather do not change substantially in spring and autumn;
2. Decreases in the occurrence of strong westerly streams in summer and autumn;
3. Changes to synoptic patterns are not expected to restrict future opportunities for prescribed burning.

<u>Vegetation change</u>

The pathway model consolidates current understanding in the field into an interactive framework, enabling plausible futures to be explored. It could be used as a tool in community adaptation, to frame potential futures and identify the consequences of decisions seeking to manage fire risk in the future. The vegetation model illustrates the potential impact of fire frequency on vegetation type, potential future fire activity, and the proportion of Tasmania that will require fuel management in the future. It shows:

1. Fire frequency has a large impact on future fire activity relative to the impact of the changing climate over the coming decades;
2. Frequent fire has the potential to lead to shifts in vegetation type, away from mesic, fire-sensitive types, towards drier, more fire-adapted vegetation;
3. The rate of change differs across vegetation types, leading to changes in vegetation structure and flammability at the landscape scale;

The results presented in this report have important consequences for the ability to manage bushfire risk using prescribed burning in the future. It is likely that there will be a narrower window of suitable conditions for burning. The changes are likely to constrain the application of prescribed burning in the autumn months, currently the period when the majority of prescribed burns are carried out. Changes to the timing of prescribed burning may be necessary, towards the winter and early spring months. As the viability of prescribed burning in some areas and times will decrease, it may need to be supplemented by other fuel reduction techniques under future climate conditions.

Implications for the viability of prescribed burning in Tasmania under ongoing climate change
It is likely that there will be a narrower window of suitable conditions for prescribed burning in the future.
Increases in temperature and fuel availability and decreases in fuel moisture are projected to occur across Tasmania in spring and autumn.
The trends are a continuation of observed changes over recent decades.
Changes become evident in the near future (2021-2040), and lead to very substantial changes by the end of the century under a high emission scenario.
The timing and resourcing of prescribed burning will be affected, and alternative methods to build resilience to bushfire risk will need to be considered.

Introduction

Research recently completed by the Antarctic Climate and Ecosystems CRC suggests that fire danger may increase across much of Tasmania under ongoing climate change, with the fire season starting earlier in the year, and lasting for longer (Fox–Hughes et al. 2015). This research found that changes to fire danger vary across Tasmania and in different seasons, most notably with an increase in high fire danger days projected to occur in spring.

This has important consequences for the ability to manage bushfire risk using prescribed burning, which is currently the only effective method of managing bushfire risk at the landscape scale in Tasmania. Prescribed burning is extensively used to reduce fuel loads and bushfire risk around human assets, particularly in the peri-urban fringe. It is also used to manage biodiversity and protect fire sensitive habitats in many National Parks and the Tasmanian Wilderness World Heritage Area (TWWHA). It is usually carried out in the autumn when weather conditions and soil moisture are conducive to safe, low intensity burning. To perform planned burning safely, the fire intensity, average flame and scorch height need to be constrained. This means that burning can only be carried out under specific weather conditions, which are determined by wind speed and direction, fuel moisture, relative humidity, soil moisture and temperature (Marsden-Smedley 2009). If the window during which suitable conditions occur becomes narrower under future climate conditions, the viability of prescribed burning as a management tool will be compromised.

This report outlines a study designed to investigate changes to weather conditions that are appropriate for prescribed burning in Tasmania under climate change. The study investigated three aspects that could affect the future viability of prescribed burning:

Part 1 is an assessment of changes in the factors that determine when prescribed burning can be applied (rainfall, temperature, fuel moisture and atmospheric stability). Changes in seasonal and monthly values between current and future time periods in the Climate Futures for Tasmania (CFT) projections are assessed;

Part 2 is a description of daily weather patterns related to extreme fire danger, and an overview of how these may change in the future. Changes in the frequency and distribution of daily weather patterns associated with high levels of atmospheric instability and extreme fire danger are investigated. This will enable us to focus on particular months and seasons when prescribed burning is applied in Tasmania. Understanding projected changes to the synoptic patterns across the seasons will highlight changing opportunities or restrictions on prescribed burning in different regions of Tasmania at different times of the year, from now into the future.

Part 3 describes changes to broad vegetation types caused by the interaction between climate change and frequency of burning (natural or prescribed). A vegetation model is developed to provide an indication of the future trajectory of vegetation, allowing gradual change to flammability across the landscape to be incorporated into longer-term planning and the consequences of prescribed burning to be considered.

General Methods - Climate Futures for Tasmania projections
The analyses are based on the Climate Futures for Tasmania (CFT) projections (Corney et al. 2010), which provide fine-scale (10 km) model output of key climate variables to inform impacts of projected climate change over Tasmania. **The projections were dynamically downscaled using sea surface temperature from six different atmosphere-ocean general circulation models from the Coupled Model Intercomparison Project archive (CMIP3) under the A2 emissions scenario as boundary conditions into the CSIRO Cubic Conformal Atmospheric Model. The host models were: ECHAM5/MPI-OM, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2(medres), UKMO-HadCM3 and CSIRO-Mk3.5. These models give slightly different results because they are based on different configurations, but all represent plausible representations of the future climate.** **Dynamically downscaled climate models represent the climate processes that operate over small distances, so they have the potential to capture regional variation in the climate change signal. This is particularly relevant in Tasmania, which has a complex topography and coastline, and a range of regional climate influences.** **To incorporate the uncertainty due to the range in climate models, we present the results from the two models that give the highest and lowest value of each variable. The multi-model mean is also presented. Averaging the six models smooths out the annual and decadal components of natural variability and reveals the forced climate response independent of the different model configurations.** **The high emissions scenario (A2) is used because global emissions are currently tracking at the higher level of this scenario (Peters et al. 2013). If strong mitigation policies were to achieve reductions in global greenhouse emissions, the pattern of projected changes would be similar, but lower in magnitude.**

Climate Futures for Tasmania – Comparison of changes projected by the Climate Futures for Tasmania project and CMIP5 archives

The Climate Futures for Tasmania (CFT) projections were completed in 2011 using the most up-to-date climate models available at the time. The global climate models came from the archive of Phase three of the Coupled Model Intercomparison Project (CMIP3), which coordinated the work of modelling groups from around the world to provide the science basis for the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007). Since then, a new archive of climate models has been developed by the World Climate Research Programme's Working Group on Coupled Modelling. The CMIP5 model archive underpins the science of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2014). However, model development and addition of new models has not led to any major revision of the conclusions drawn from work using CMIP3. Regional comparisons of the CMIP3 and CMIP5 projections for Australia have found them to give largely consistent results for temperature, rainfall, wind speed, humidity, solar radiation and potential evapotranspiration (Irving et al. 2012, Lee et al. 2013, CSIRO and Bureau of Meteorology 2015).

The CFT results were produced using one downscaling technique (CCAM), and used input from six Global Climate Models (GCMs) out of the set of 23 CMIP3 models available. The six models have been assessed against the full group of 23, and have been shown to be fairly representative of the archive. They cover a range of plausible futures, and do not only include models at one extreme end of the projections for Tasmania or southeast Australia for any season (Grose et al. 2015a).

Grose et al. (2015c) compared the CFT outputs with those from a statistical downscaling method (BOM-SDM) and from GCMs at resolutions of 100-250 km. They found that CFT produced greater regional detail and regional patterns of change which are consistent with topographic influences and regional drivers that are not resolved by coarse global models. These patterns include a difference in the range of projected rainfall change in the east of Tasmania compared to the west in some seasons. This 'added value' in the projected change is the main advantage of using the CFT projections.

Grose et al. (2015a; 2015b) compared the Climate Futures for Tasmania projections with a range of CMIP3 models, CMIP5 models, and new downscaling (~50 km) using a more recent version of the CCAM model than that used in the Climate Futures for Tasmania project. For Tasmania, the report concluded that once the difference in emissions scenarios is accounted for:

Projections of <u>temperature</u> from the Climate Futures for Tasmania project "are broadly consistent with the new CMIP5 results" (Grose et al. 2015a, pg 20).

The Climate Futures for Tasmania projections of <u>annual rainfall</u>, and <u>summer</u>, <u>autumn</u> and <u>winter rainfall</u> show similar trends to the new models. However, the CFT results show little trend in <u>spring rainfall</u> across Tasmania, while other models project a decrease in spring rainfall. This suggests that the CFT results across Tasmania "are at the wetter end of the plausible range of spring rainfall projections" (Grose et al. 2015a, pg 28). The results presented in this report are therefore likely to be conservative estimates of projected changes in spring rainfall.

Projections of <u>heavy rainfall</u> in the Climate Futures for Tasmania results "are supported by the CMIP5 results." (Grose et al. 2015a, pg 29)

Part 1: An assessment of changes in the factors that determine when prescribed burning can be applied

1.1 Introduction

Prescribed burning can only be applied under specific weather conditions that enable fires to be managed safely and meet fire management objectives (Marsden-Smedley 2009). These conditions include wind speed, atmospheric stability and fuel moisture, which directly influence fire behaviour. Fire behaviour is also indirectly affected by relative humidity, temperature, Drought Factor (DF) and Soil Dryness (SDI) through their influences on fuel moisture.

1.2 Methods

The projected change in these variables for each month are calculated between the baseline period (1961-1980) and two future time periods, near future (2021-2040) and the end of century (2081-2100). Trends are averaged spatially across Australian Bureau of Meteorology weather forecast districts (Figure 1.1), within each of which the climate is broadly similar. These values were further averaged over two-decade periods, to reduce the effect of inter-annual variability and to highlight longer-term climate trends.

The Drought Factor (an index scaled between 0 and 10) represents the influence of recent temperatures and rainfall events on fuel availability. It is calculated by combining estimates of the effects of (a) direct wetting from recent ‘significant’ rainfall (> 2mm); and (b) wetting from below, which is dependent on the soil moisture content. The latter is calculated as a soil moisture deficit, using the Soil Dryness Index (SDI) (Mount 1972). The Soil Dryness Index (SDI) is also used as an index of fuel moisture. It is used operationally to help assess the relative flammability of different vegetation types, and therefore the ability to safely conduct a prescribed burn.

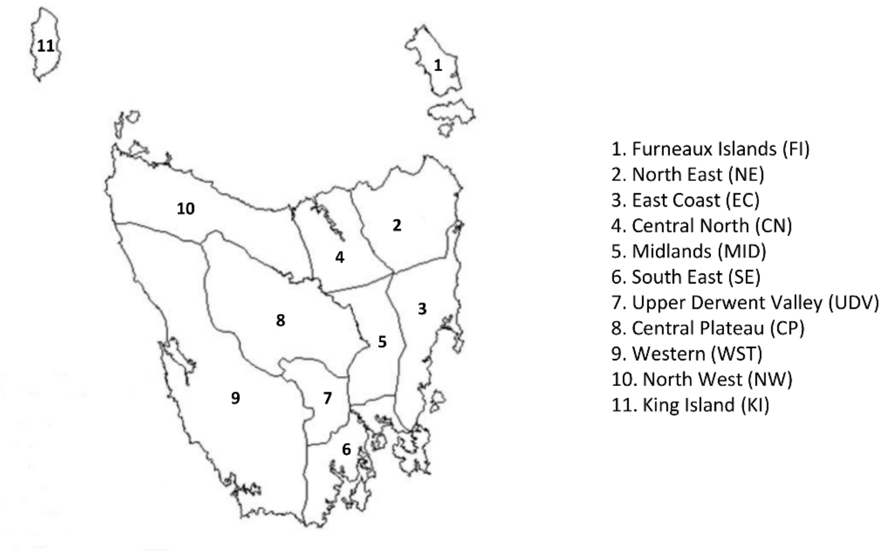


Figure 1.1: Bureau of Meteorology weather forecast districts over which the climate variables are summarised in this report.

1.3. Results

Changes to seasonality between current and future time periods

To identify any changes in seasonality in the future, seasonal and monthly values for temperature, rainfall, relative humidity, Drought Factor (DF), Soil Dryness Index (SDI), atmospheric stability and wind speed and direction are averaged over Tasmania and over each of the Bureau of Meteorology weather forecast districts.

Changes in climate variables vary in the different regions of Tasmania (Figure 1.2). State-wide trends projected for Tasmania are presented in the main body of the report, and results for each forecast district are presented in Appendix A. These are intended to provide a resource for investigating projected changes at a finer scale.

The multimodel mean and model range (minimum and maximum values of the six climate models) for annual and seasonal values are summarised in Table 1.1 and Table 1.2. Trends in each variable are discussed separately in the following sections. The implications of these results for the effectiveness of prescribed burning as a management tool in the future are discussed in Section 1.4.

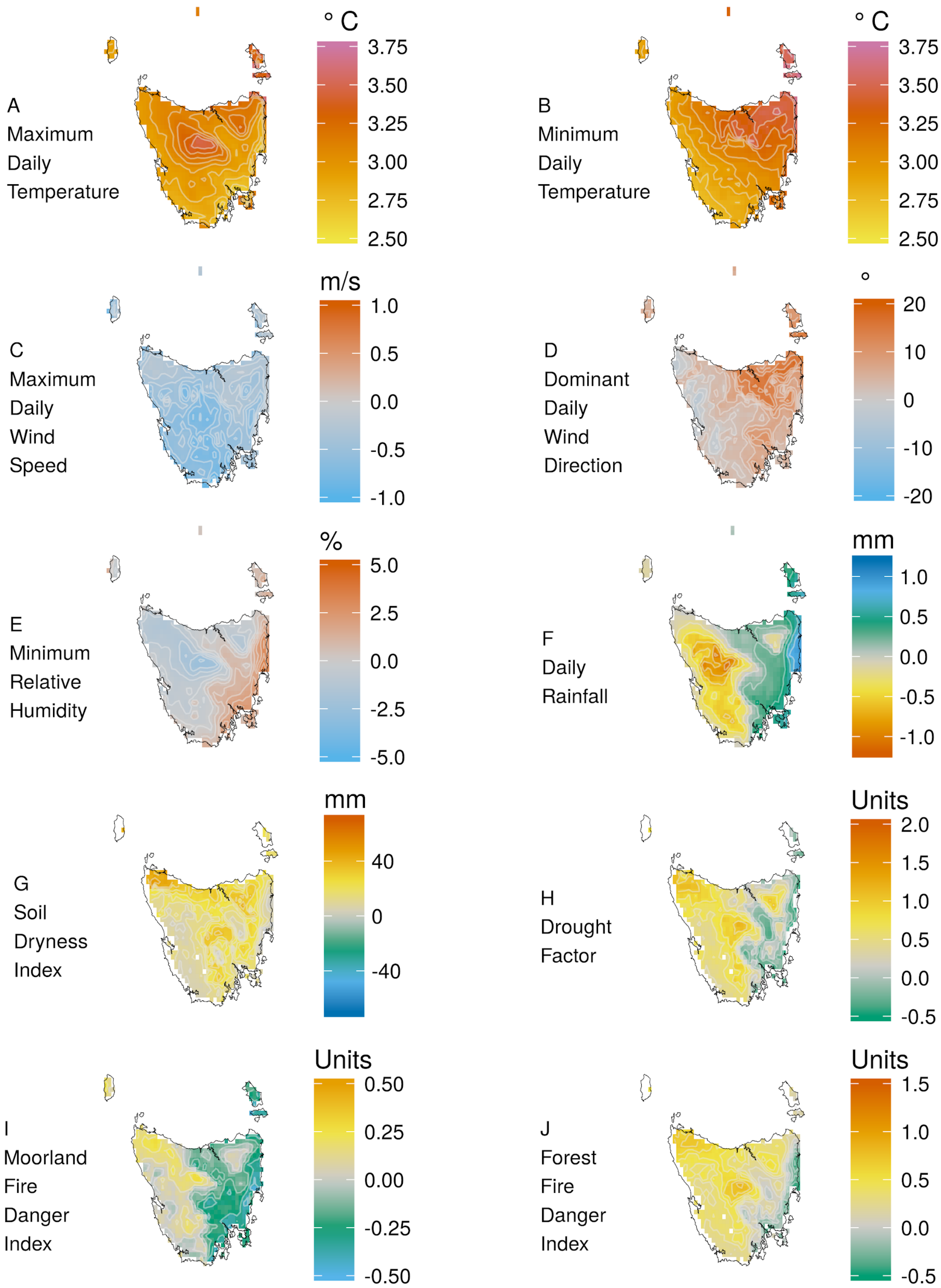


Figure 1.2: Change in climate variables for the autumn period by 2071-2100, relative to the baseline period (1961-1980). Positive values for wind direction indicate a clockwise wind direction, negative indicates anti-clockwise

Table 1.1: Range in climate variables projected by the six climate models. The multi-model mean is shown for each 20-year period over all grid cells in Tasmania, with the range of means between climate models shown in brackets. Wind direction is degrees clockwise from North.

Period	**Season**	**Min. Temp. (°C)**		**Max. Temp. (°C)**		**Wind Speed (m/s)**		**Wind Direction (°)**		**Min. Rel. Humidity (%)**		**Rainfall (mm/month)**	
		mean	range	mean	range	mean	range	mean	range	mean	range	mean	range
1961-1980	Annual	6	(6,6)	15	(15,15)	7	(7,7)	130	(128,131)	66	(66,66)	109	(106,111)
	Spring	6	(4,7)	15	(12,17)	7	(6,8)	128	(124,132)	64	(57,70)	115	(89,142)
	Summer	9	(9,10)	20	(18,21)	6	(6,7)	135	(130,143)	54	(52,59)	78	(55,107)
	Autumn	7	(5,9)	16	(13,19)	7	(6,8)	128	(119,138)	70	(61,77)	103	(76,137)
	Winter	3	(3,4)	11	(10,11)	8	(7,8)	128	(121,137)	76	(73,78)	139	(124,164)
1981-2000	Annual	7	(7,7)	15	(15,15)	7	(7,7)	130	(128,130)	66	(66,66)	108	(107,110)
	Spring	6	(5,8)	15	(12,17)	7	(6,8)	130	(121,137)	64	(57,70)	113	(89,141)
	Summer	10	(9,10)	20	(18,21)	6	(6,7)	134	(128,143)	55	(51,59)	79	(56,104)
	Autumn	7	(6,9)	16	(13,19)	7	(6,7)	128	(119,141)	70	(62,76)	102	(80,131)
	Winter	4	(3,4)	11	(10,11)	8	(7,8)	126	(121,134)	76	(73,78)	137	(123,150)
2001-2020	Annual	7	(7,7)	16	(16,16)	7	(7,7)	129	(128,130)	66	(65,66)	108	(104,114)
	Spring	6	(5,8)	15	(13,18)	7	(6,8)	131	(119,145)	63	(57,71)	112	(84,145)
	Summer	10	(9,11)	20	(19,21)	6	(6,8)	131	(120,138)	54	(51,57)	76	(54,94)
	Autumn	8	(6,9)	16	(13,20)	7	(6,8)	128	(118,140)	70	(62,76)	104	(78,136)
	Winter	4	(3,5)	11	(10,12)	7	(6,8)	127	(119,141)	76	(73,78)	138	(129,154)
2021-2040	Annual	7	(7,8)	16	(16,16)	7	(7,7)	130	(128,131)	66	(65,66)	108	(104,115)
	Spring	7	(5,8)	15	(13,18)	7	(6,8)	130	(123,147)	64	(57,70)	114	(90,148)
	Summer	11	(9,11)	21	(19,22)	7	(6,8)	132	(122,144)	55	(52,58)	80	(58,100)
	Autumn	8	(6,10)	17	(13,20)	7	(6,8)	127	(115,144)	70	(62,77)	101	(75,150)
	Winter	4	(4,5)	12	(11,12)	7	(6,8)	129	(121,146)	76	(73,78)	137	(129,151)
2041-2060	Annual	8	(8,8)	17	(16,17)	7	(7,7)	130	(130,131)	66	(65,67)	108	(100,116)
	Spring	7	(6,9)	16	(13,19)	7	(6,8)	125	(121,133)	63	(55,70)	112	(80,141)
	Summer	11	(10,12)	21	(20,22)	7	(6,8)	133	(121,146)	55	(50,57)	78	(57,101)
	Autumn	9	(7,11)	17	(14,21)	6	(6,7)	131	(117,147)	70	(62,77)	102	(75,137)
	Winter	5	(4,6)	12	(11,13)	7	(6,9)	131	(124,149)	76	(74,79)	140	(125,157)
2061-2080	Annual	9	(8,9)	17	(17,18)	7	(7,7)	131	(129,132)	66	(65,66)	109	(106,117)
	Spring	8	(6,10)	17	(14,19)	8	(6,8)	124	(119,133)	63	(54,69)	113	(82,140)
	Summer	12	(11,13)	22	(20,23)	6	(6,8)	136	(120,147)	54	(51,58)	78	(59,110)
	Autumn	9	(7,12)	18	(15,22)	6	(6,7)	135	(118,157)	70	(60,77)	100	(61,143)
	Winter	6	(5,7)	13	(12,13)	8	(6,9)	127	(121,145)	76	(73,78)	145	(128,169)
2081-2100	Annual	9	(9,10)	18	(18,18)	7	(7,7)	130	(126,134)	66	(65,66)	110	(107,118)
	Spring	8	(7,10)	17	(14,21)	8	(6,9)	122	(117,132)	63	(54,70)	115	(80,142)
	Summer	13	(11,13)	23	(21,24)	6	(6,7)	139	(129,147)	53	(49,56)	71	(53,100)
	Autumn	10	(8,12)	19	(15,22)	6	(6,7)	135	(116,154)	70	(61,77)	102	(65,138)
	Winter	6	(5,8)	13	(13,14)	8	(6,9)	123	(116,129)	76	(73,78)	151	(130,170)

Table 1.2: Range in climate indices projected by the six climate models. The multi-model mean is shown for each 20-year period over all grid cells in Tasmania, with the range between climate models shown in brackets. Abbreviations are SDI – Soil Dryness Index, DF – Drought Factor, FFDI – Forest Fire Danger Index, MFDI – Moorland Fire Danger Index.

Period	**Season**	**SDI (mm)**		**DF**		**FFDI**		**MFDI**	
		mean	range	mean	range	99^{th}	range	99^{th}	range
1961-1980	Annual	31	(30,34)	4	(4,4)	15	(14,15)	14	(14,15)
	Spring	19	(13,27)	4	(3,5)	15	(9,23)	15	(14,16)
	Summer	45	(31,60)	5	(5,6)	28	(24,32)	15	(14,17)
	Autumn	44	(30,59)	5	(4,6)	11	(6,20)	14	(13,15)
	Winter	18	(13,25)	3	(3,4)	5	(5,7)	13	(12,15)
1981-2000	Annual	32	(29,35)	4	(4,4)	15	(15,15)	15	(14,15)
	Spring	20	(13,28)	4	(3,4)	16	(9,23)	15	(15,16)
	Summer	46	(30,64)	5	(4,6)	28	(20,32)	15	(14,16)
	Autumn	44	(29,62)	5	(4,6)	11	(6,19)	14	(13,15)
	Winter	19	(13,26)	3	(3,4)	6	(5,7)	14	(12,14)
2001-2020	Annual	34	(32,37)	4	(4,5)	16	(15,16)	15	(14,15)
	Spring	22	(14,30)	4	(3,5)	16	(10,24)	15	(15,17)
	Summer	49	(35,67)	6	(5,6)	28	(23,36)	15	(14,16)
	Autumn	46	(30,65)	5	(4,6)	11	(6,19)	14	(13,14)
	Winter	19	(13,27)	3	(3,4)	6	(5,7)	14	(13,15)
2021-2040	Annual	35	(29,40)	4	(4,5)	15	(14,16)	14	(14,15)
	Spring	23	(13,33)	4	(3,5)	16	(10,24)	15	(14,16)
	Summer	50	(34,67)	6	(5,6)	28	(23,34)	15	(14,16)
	Autumn	47	(26,69)	5	(4,6)	11	(6,18)	13	(13,14)
	Winter	21	(13,32)	3	(3,4)	6	(5,8)	14	(13,15)
2041-2060	Annual	38	(31,43)	4	(4,5)	16	(15,17)	15	(14,15)
	Spring	24	(16,38)	4	(3,5)	17	(11,26)	16	(15,17)
	Summer	54	(36,76)	6	(5,6)	29	(26,35)	15	(14,16)
	Autumn	51	(26,70)	5	(4,6)	12	(6,20)	14	(12,15)
	Winter	22	(13,34)	3	(3,4)	6	(4,8)	14	(13,16)
2061-2080	Annual	41	(37,45)	5	(4,5)	17	(16,18)	15	(14,15)
	Spring	26	(18,36)	4	(3,5)	19	(11,30)	16	(15,17)
	Summer	58	(37,79)	6	(5,6)	29	(24,34)	15	(14,15)
	Autumn	56	(35,82)	5	(4,7)	12	(6,24)	14	(13,15)
	Winter	23	(16,38)	3	(3,4)	6	(5,9)	14	(13,16)
2081-2100	Annual	46	(41,52)	5	(4,5)	17	(17,18)	15	(15,15)
	Spring	29	(18,44)	4	(3,5)	20	(11,31)	16	(15,18)
	Summer	69	(47,95)	6	(5,7)	31	(27,36)	15	(13,16)
	Autumn	63	(37,93)	5	(4,7)	12	(6,20)	13	(12,14)
	Winter	25	(16,42)	3	(3,4)	7	(5,10)	15	(13,17)

1.3.1 Temperature

Mean annual temperature increases of approximately 1°C and 2.7°C are projected to occur over Tasmania in the near future (2021-2040) and end of the century (2081-2100) periods respectively under the high emissions scenario considered here (SRES A2) (Table 1.1). This is a gradual continuation of warming trends observed over recent decades. These increases are consistent across the seasons (Figure 1.3).

Increases in maximum and minimum daily temperature are evident in every month of the year across Tasmania (Figure 1.4). Over the next decades, monthly temperatures are projected to move towards temperatures currently experienced in warmer months. By the end of the century, the increase in maximum temperature in September and October is approximately equal to a shift of one month towards summer. So, by 2081-2100, temperatures in September will be more like those currently experienced in October, and those in October will be more like those currently experienced in November. The shift in the autumn months is of a similar magnitude, so temperatures in April may be more like those currently experienced in March, and those in May will be more like those currently experienced in April. However, the relative shift is greater in other months. Future November maximum temperatures are closer to those currently experienced in February, and during the winter months, maximum temperatures by the end of century will be more similar to those currently in mid-spring. Mean increases in minimum temperatures are slightly higher than those in maximum temperature, with a two-month shift towards warmer months across the year, except during summer, when mean minimum temperatures exceed any currently experienced.

By the end of the century, days exceeding the 25°C threshold above which prescribed burning cannot be applied are projected to occur regularly in November, while they currently only occur regularly in December, January and February.

The multi-model mean of annual temperature change is similar across Tasmania, and the rate of change in temperature is similar across all the BoM forecast districts (Table 1.3, 1.4). However, there are seasonal differences in different districts. Parts of the East Coast and Central Plateau districts are projected to experience the greatest increases in spring temperatures (Figure 1.5). The North East, Central North and Central Plateau districts are projected to experience the greatest increases in autumn temperatures (Appendix 1A).

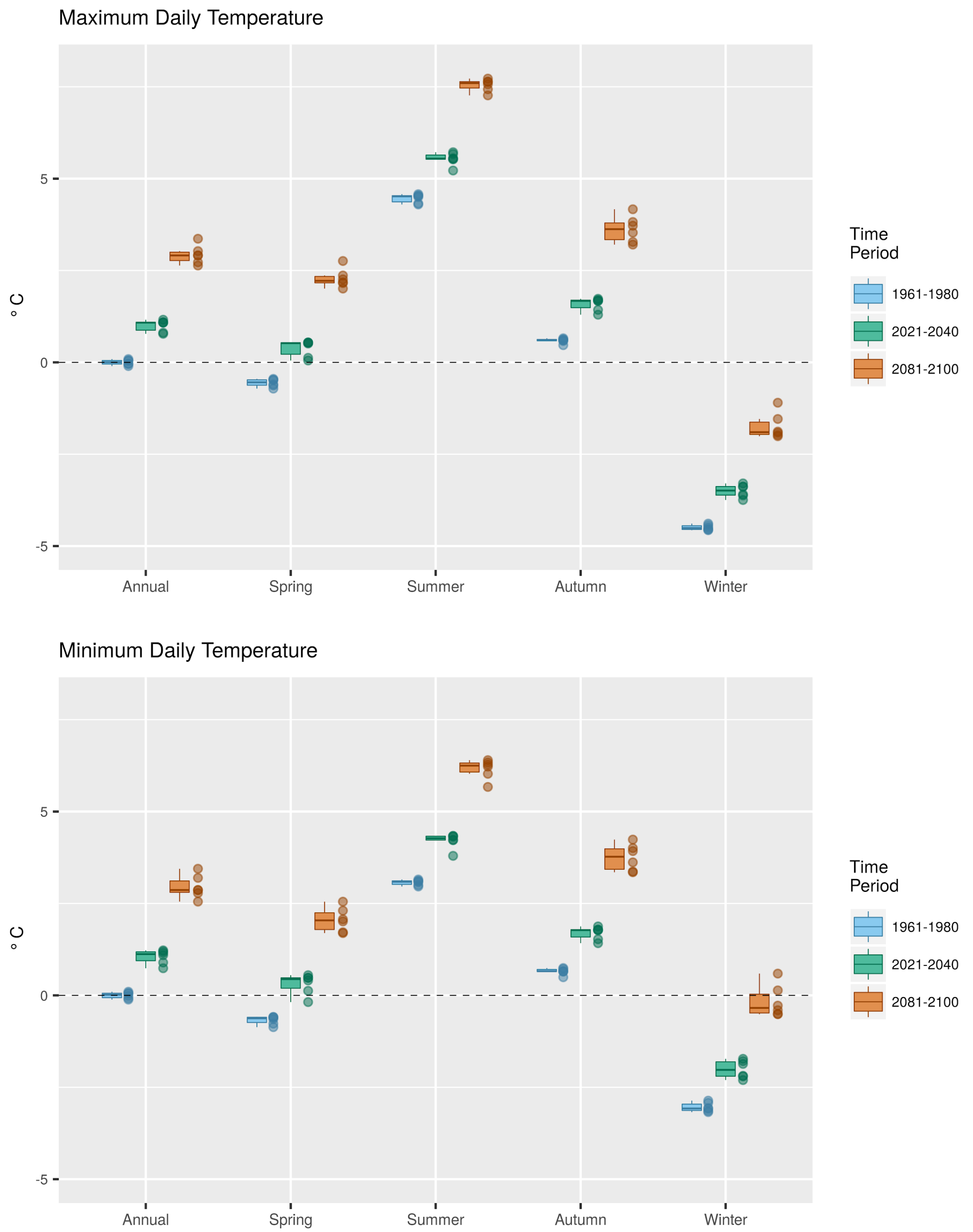


Figure 1.3: Six-model summary of changes in daily maximum and minimum temperature across Tasmania under the A2 emission scenario for each season in the baseline (1961-1980), near future (2021-2040) and end of century periods (2081-2100). Values represent change from the multi-model mean annual value for the baseline period. The box indicates the multi-model range, the bar shows the mean of all models, and ticks indicate the mean for each of the six downscaled climate models.

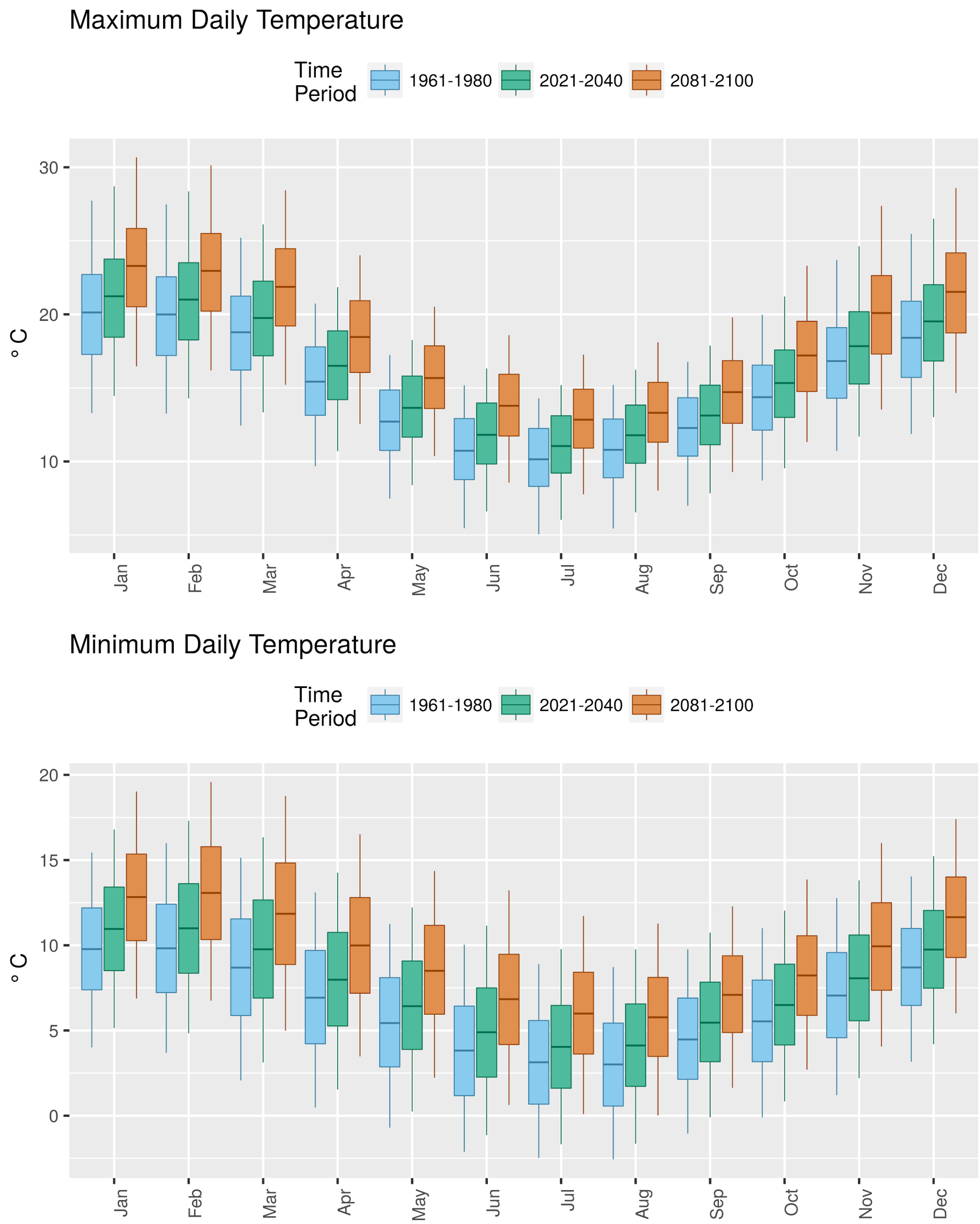
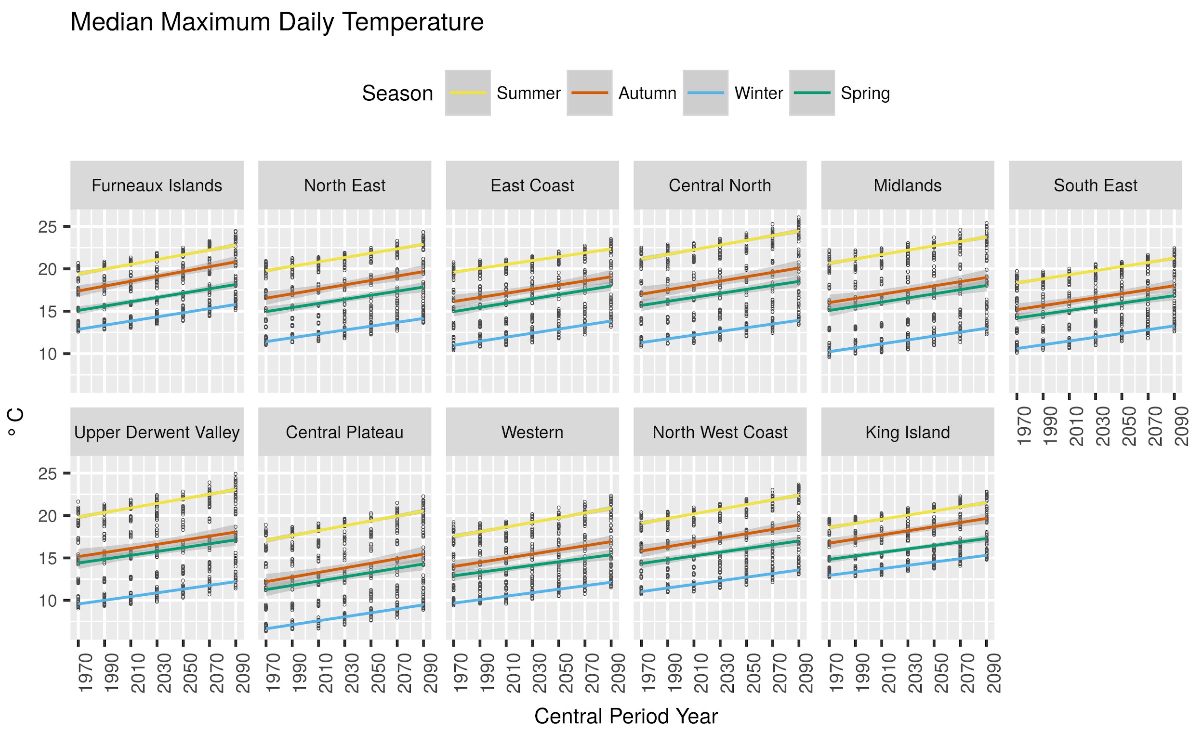


Figure 1.4: Annual cycle of maximum and minimum daily temperature projected by the six climate models for the baseline (1961-1980), near future (2021-2040) and end of century (2081-2100) periods. The box indicates the interquartile range, the bar shows the mean, and the whiskers extend from the 5^{th} to the 95th percentile.



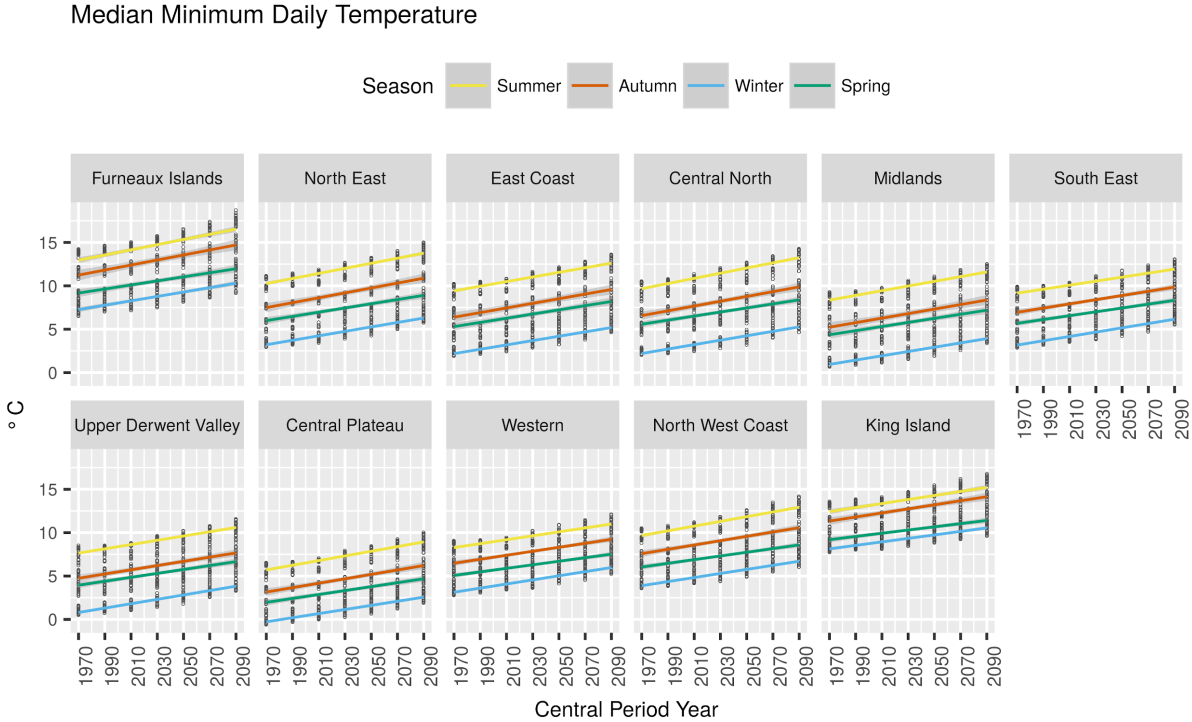


Figure 1.5: Trends in seasonal maximum and minimum daily temperature projected by the six climate models in 20-year periods from 1961 to 2100 in each of the BoM forecast districts. Black dots represent one value for each of the six models in each season. The grey shadow represents the weighted mean square error of the regression.

Table 1.3: Rate of change (°C per year) in Maximum Daily Temperature in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.5.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	0.027	0.028	0.026	0.026
North East	0.026	0.026	0.023	0.025
East Coast	0.023	0.024	0.024	0.026
Central North	0.027	0.026	0.022	0.024
Midlands	0.025	0.024	0.023	0.025
South East	0.024	0.024	0.023	0.023
Upper Derwent Valley	0.026	0.024	0.023	0.023
Central Plateau	0.028	0.027	0.024	0.025
Western	0.026	0.024	0.021	0.021
North West Coast	0.027	0.025	0.021	0.022
King Island	0.023	0.024	0.020	0.021

Table 1.4: Rate of change (°C per year) in Minimum Daily Temperature in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.5.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	0.029	0.029	0.026	0.025
North East	0.029	0.028	0.025	0.024
East Coast	0.027	0.027	0.024	0.025
Central North	0.030	0.028	0.025	0.024
Midlands	0.027	0.026	0.023	0.024
South East	0.024	0.025	0.025	0.023
Upper Derwent Valley	0.025	0.025	0.025	0.023
Central Plateau	0.027	0.025	0.023	0.023
Western	0.023	0.024	0.024	0.021
North West Coast	0.028	0.026	0.023	0.022
King Island	0.024	0.024	0.020	0.019

1.3.2 Rainfall

Annual mean rainfall is not projected to change substantially across Tasmania in the future, however there are strong seasonal (Figures 1.6 and 1.7) and regional differences in the projected rainfall (Figure 1.8). Summer rainfall is projected to decline in four of the six models, and winter rainfall is projected to increase substantially in all models. There is little change projected in the mean rainfall in autumn. Five of the six models project increased mean monthly rainfall in spring, while one projects reduced rainfall during this season.

The CFT spring rainfall projections should be considered in the context of other available climate projections. As discussed in Box 2, Grose et al. (2015a; 2015b) compared the Climate Futures for Tasmania projections with a range of CMIP3 models, CMIP5 models, and new downscaling (~50km) using a more recent version of the CCAM model than that used in the Climate Futures for Tasmania project. While the Climate Futures for Tasmania projections of annual rainfall, and summer, autumn and winter rainfall show similar trends to the new models, the spring projections differ slightly. The CFT results show little trend in spring rainfall across Tasmania, while other models project a decrease in spring rainfall. This suggests that the CFT results across Tasmania “are at the wetter end of the plausible range of spring rainfall projections” (Grose et al. 2015a, pg 28). The results presented in this report are therefore likely to be conservative estimates of the drying trends in spring.

When averaged across Tasmania, there is little change projected to occur in monthly rainfall (Figure 1.7). However, when the climate models are shown separately, as in Appendix A, it can be seen that there is a wide range in projections, with some climate models projecting increased rainfall and others decreased rainfall. This makes it difficult to draw conclusions about the effect of changing rainfall on the ability to apply prescribed burns in autumn and spring in several districts. Model agreement is low in the Central North, Upper Derwent, North East and South East districts, with some models projecting increases and others projecting decreases or little change in monthly rainfall (Appendix A). This degree of uncertainty is common in projections of rainfall (CSIRO and Bureau of Meteorology 2015), because the large-scale storm tracks in the projections are uncertain (Risbey and O’Kane 2011), and it is difficult to fully resolve the many physical processes involved in precipitation or the fine-scale spatial variability (Dowdy et al. 2015).

However, some seasonal trends are evident in some districts (Figure 1.8, Appendix A). There is high model agreement in several districts that project decreased rainfall by the end of the century in all spring months (Central Plateau, King Island, North West, Midlands) or in September and October (East Coast), with large declines projected in the Central Plateau district. The majority of models project increased rainfall in September and October for the Furneaux (5 of 6 models in both months), and Western districts (5 of 6 models in September, 4 of 6 models in October). There is also high model agreement for substantial reductions in autumn rainfall in the Western district.

The Central Plateau is projected to experience the fastest decline in autumn and spring rainfall, while other districts, such as the East Coast, Upper Derwent and South East districts, have little change projected for these seasons (Table 1.5). All districts, with the exception of the East Coast, have increased monthly rainfall during winter.

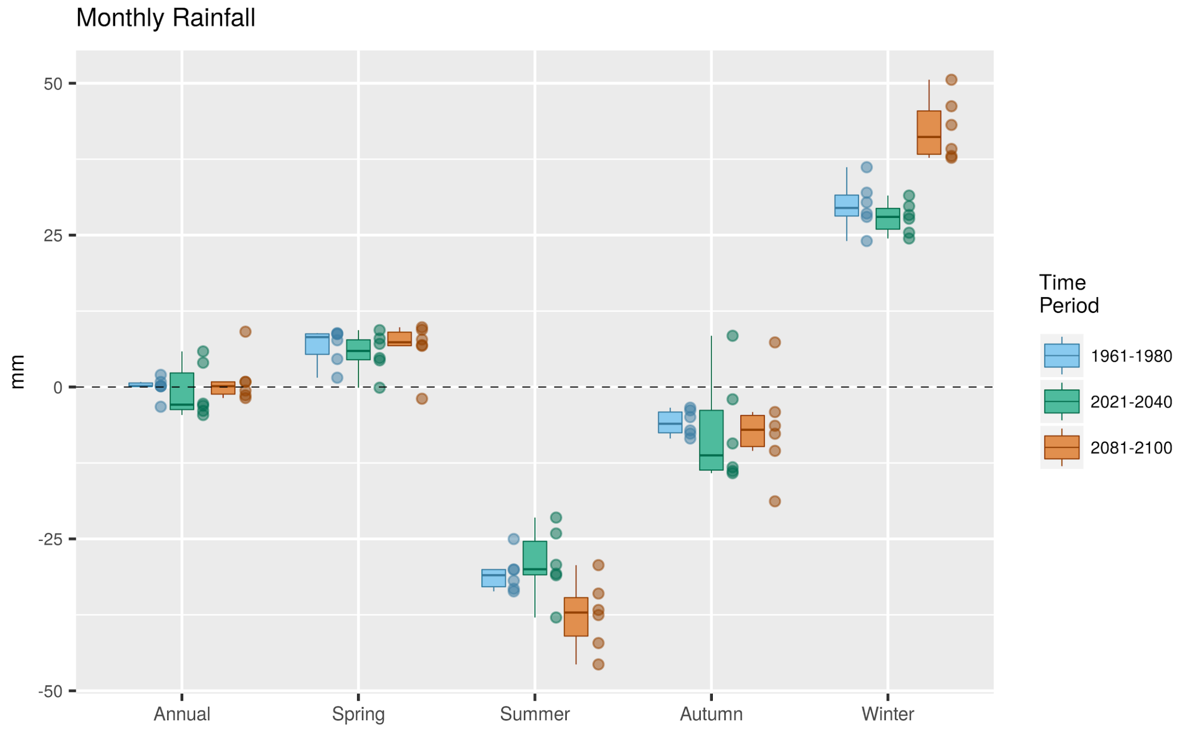


Figure 1.6: Six-model summary of changes in mean monthly rainfall (mm) averaged over Tasmania under the A2 emission scenario for each season in the baseline (1961-1980), near future (2021-2040) and end of century periods (2081-2100). Values represent change from the multi-model mean annual value for the baseline period. The box indicates the multi-model range, the bar shows the mean, and ticks indicate the mean for each of the six downscaled climate models.

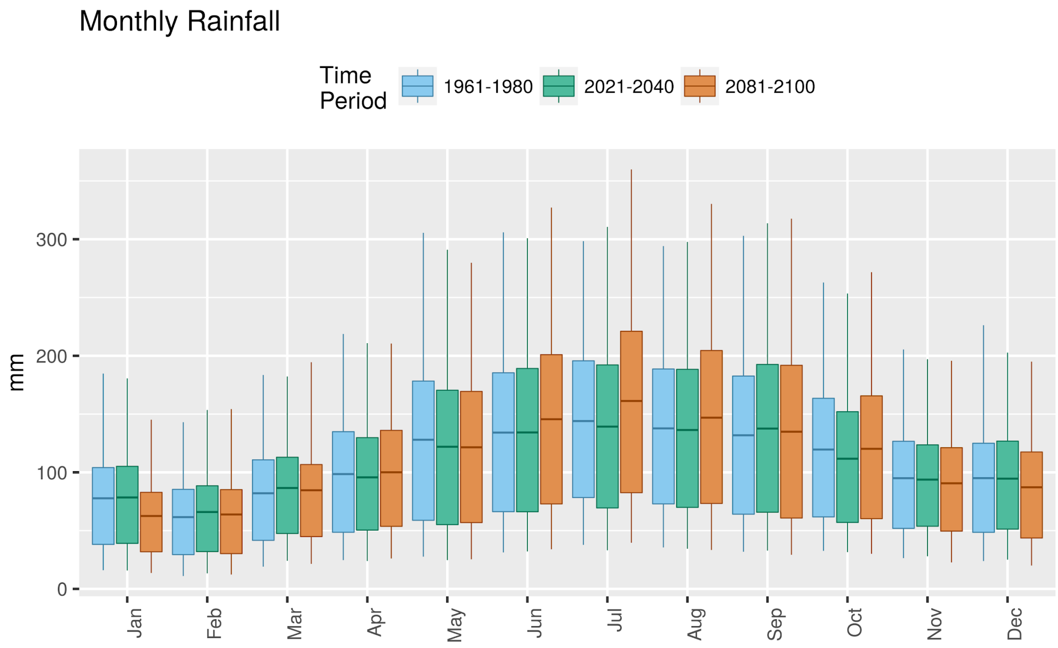


Figure 1.7: Annual cycle of monthly rainfall projected by the six climate models for the baseline (1961-1980), near future (2021-2040) and end of century (2081-2100) periods. The box indicates the interquartile range, the bar shows the mean, and the whiskers extend from the 5th to the 95th percentile.

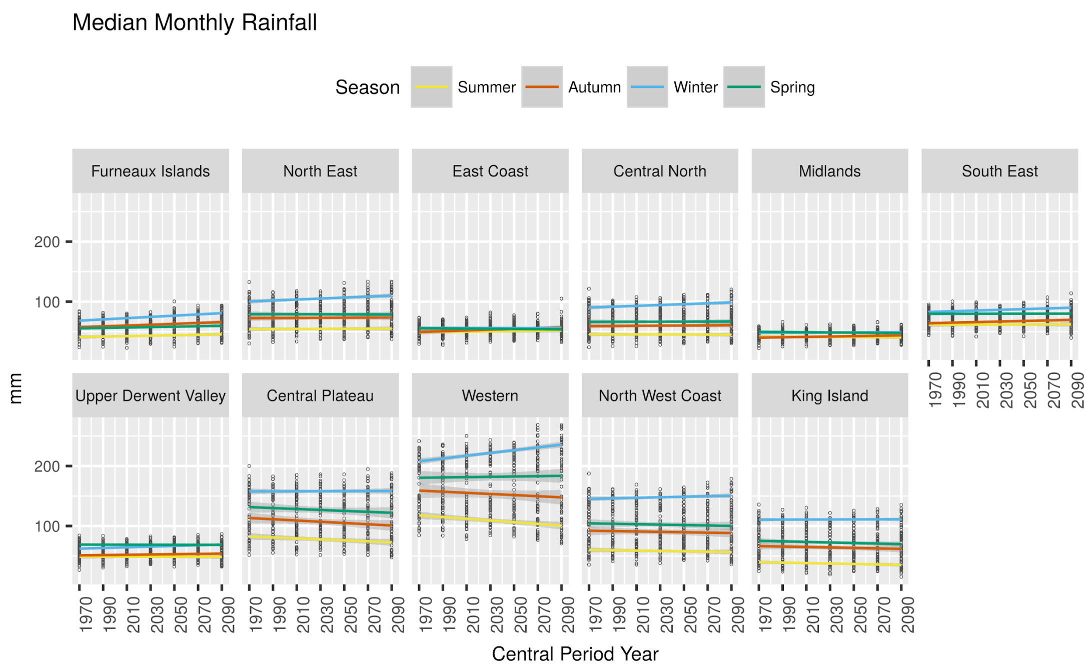


Figure 1.8: Trends in median monthly rainfall projected by the six climate models in 20-year periods from 1961 to 2100 in each of the BoM forecast districts. Black dots represent one value for each of the six models in each season. The grey shadow represents the weighted mean square error of the regression.

Table 1.5: Rate of change (mm/year) in median Monthly Rainfall in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.8.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	0.064	0.100	0.104	0.059
North East	0.032	0.029	0.090	0.011
East Coast	0.061	0.105	-0.008	-0.008
Central North	0.014	0.021	0.079	0.016
Midlands	0.016	0.046	0.015	-0.013
South East	0.023	0.047	0.045	0.004
Upper Derwent Valley	0.015	0.026	0.051	-0.001
Central Plateau	-0.094	-0.112	0.034	-0.072
Western	-0.155	-0.096	0.253	0.029
North West Coast	-0.029	-0.035	0.051	-0.038
King Island	-0.019	-0.031	0.000	-0.035

1.3.3 Drought Factor (DF)

In the near future period (2021-2040), the annual drought factor is highly variable, reflecting the greater variability in rainfall in the short-term, particularly in summer and autumn (Figure 1.9). By the end of the century, however, very substantial increases in Drought Factor are projected across Tasmania, with the greatest increases in summer. Large increases in the drought factor in spring are also projected. There is a wide range in the projections for autumn, reflecting the large range across the models in rainfall for this season.

The projections of Drought Factor across Tasmania show gradual drying trends in all months, with increases particularly during summer and early autumn (Figure 1.10).

The most rapid increase in drought factor is projected to occur in summer in the Western district (Figure 1.11, Table 1.6). In autumn, the greatest rate of increase in Drought factor is projected for King Island, Central Plateau and the North West Coast. In spring, the fastest change is projected for the Midlands, King Island and East Coast districts. The Furneaux and North East districts have the slowest rate of change projected for all seasons.

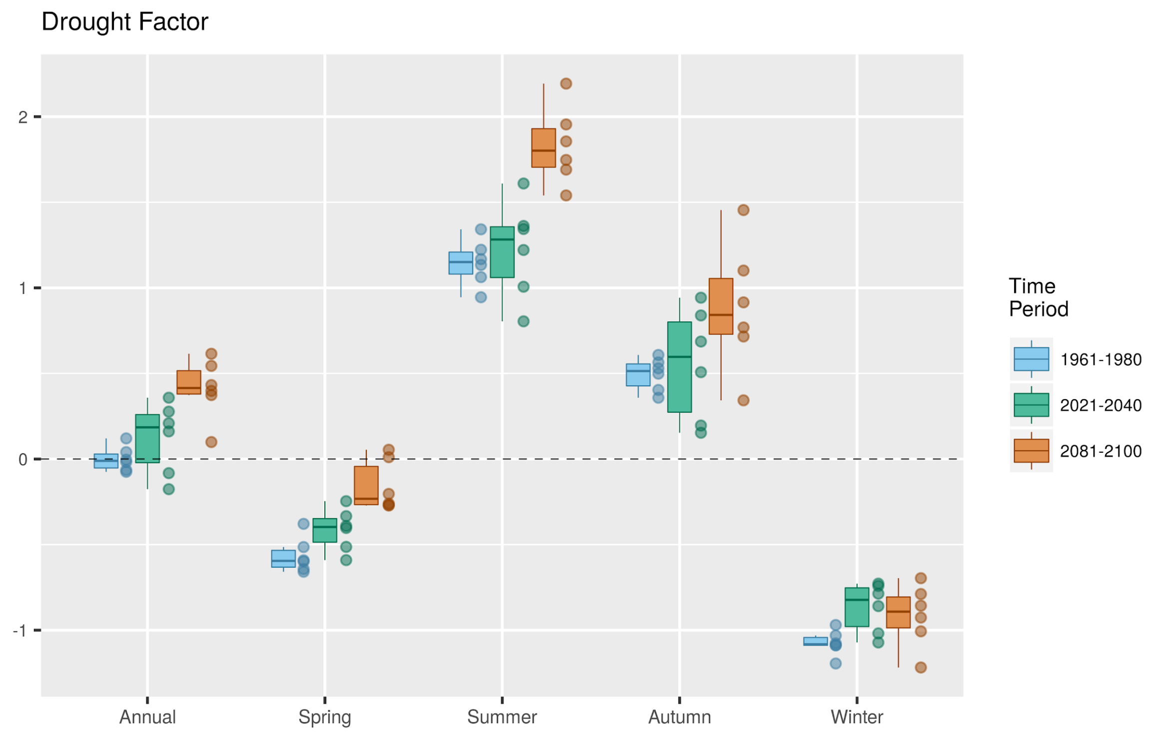


Figure 1.9: Six-model summary of changes in monthly drought factor averaged over Tasmania under the A2 emission scenario for each season in the baseline (1961-1980), near future (2021-2040) and end of century periods (2081-2100). Values represent change from the multi-model mean annual value for the baseline period. The box indicates the multi-model range, the bar shows the mean, and ticks indicate the mean for each of the six downscaled climate models.

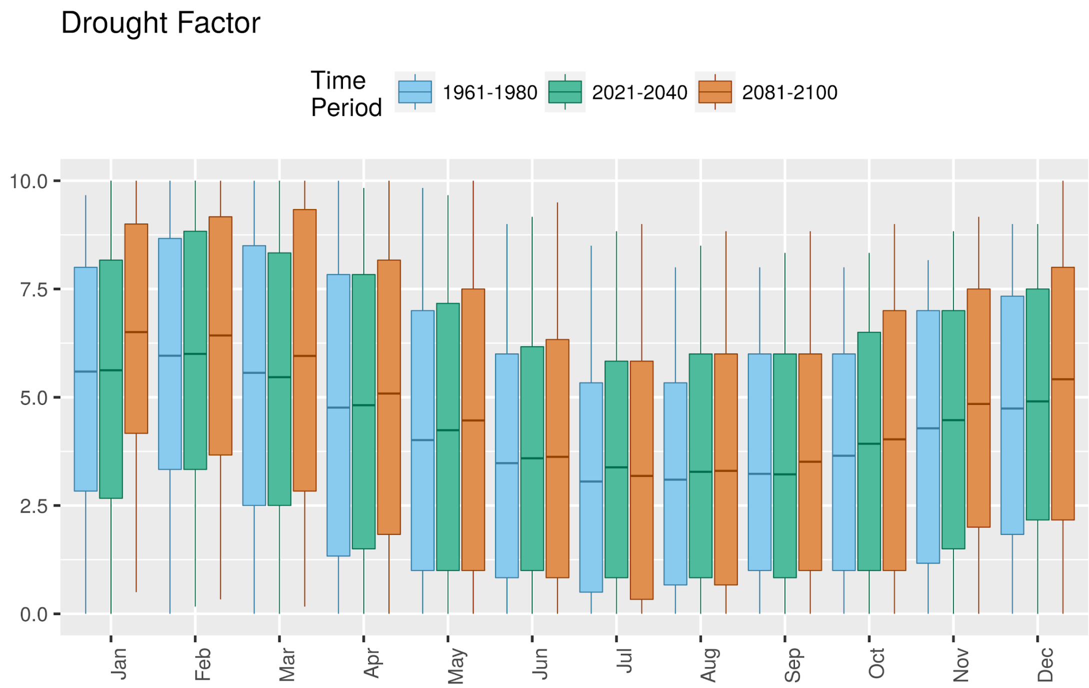


Figure 1.10: Annual cycle of drought factor projected by the six climate models for the baseline (1961-1980), near future (2021-2040) and end of century (2081-2100) periods. The box indicates the interquartile range, the bar shows the mean, and the whiskers extend from the 5th to the 95th percentile.

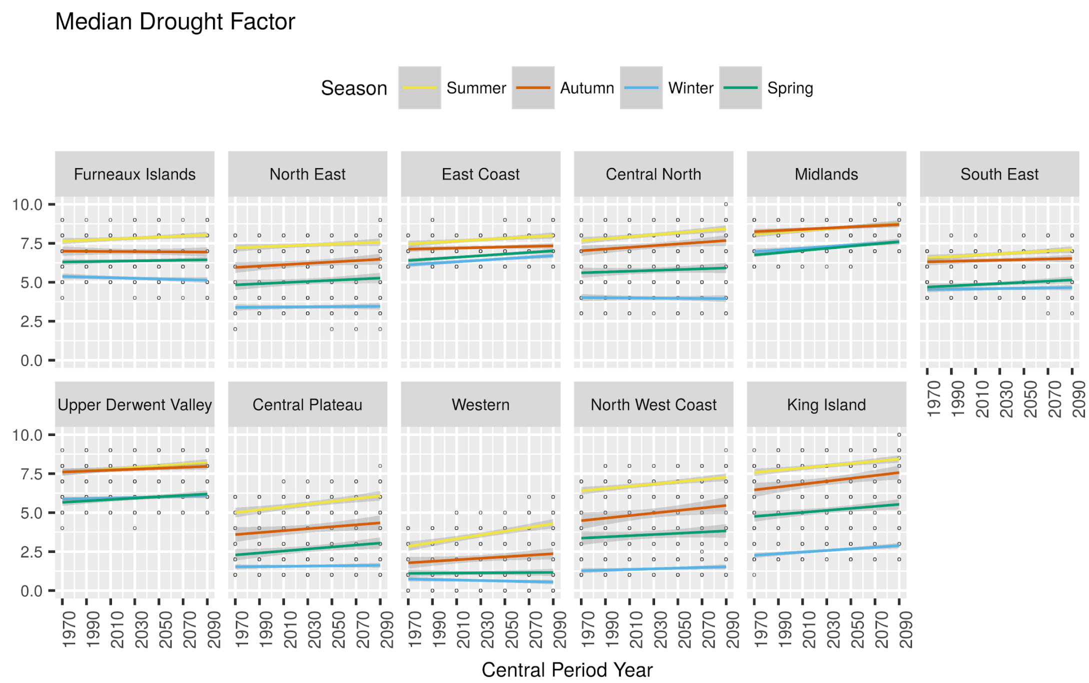


Figure 1.11: Trends in seasonal maximum and minimum daily temperature projected by the six climate models in 20-year periods from 1961 to 2100 in each of the BoM forecast districts. Black dots represent one value for each of the six models in each season. The grey shadow represents the weighted mean square error of the regression.

Table 1.6: Rate of change in Drought Factor in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.11.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	0.002	-0.000	-0.001	0.001
North East	0.003	0.003	0.001	0.003
East Coast	0.002	-0.000	0.003	0.005
Central North	0.003	0.003	0.001	0.003
Midlands	0.003	0.001	0.004	0.006
South East	0.003	0.002	0.002	0.003
Upper Derwent Valley	0.003	0.002	0.002	0.003
Central Plateau	0.007	0.006	0.002	0.004
Western	0.008	0.005	-0.001	0.001
North West Coast	0.006	0.006	0.002	0.004
King Island	0.006	0.007	0.004	0.005

1.3.4 Soil dryness index (SDI)

Substantial increases in Soil Dryness Index are projected to occur across Tasmania in the future. In the near term (2021-2040), all models project an increase in soil dryness index in summer, and all but one model project increased soil drying during spring and winter (Figure 1.12). There is a greater range across the models in autumn. However, by the end of the century, substantial increases in the soil dryness index are projected by all climate models in all seasons.

Increases in SDI are greatest in the summer and autumn months by the end of the century (2081-2100) (Figure 1.13). Smaller increases are projected in late winter and spring months. Increases in the SDI values for both June and November are so substantial that the wettest period (for SDI) is projected to be 2 months shorter by the end of century. In the current period, values of SDI greater than 125, the threshold above which prescribed burning cannot be applied safely in forests (Marsden-Smedley, 2009), only occur in February, March and April. By the mid-century period, the projections show days above 125 occur in every month from January to May, and by the end of the century, this value will be exceeded in 6 months of the year, from December through to May.

Change is projected to occur rapidly over the next decades, with the fastest rate of change in the Midlands and the East Coast districts in spring, and in King Island, North West Coast and Central North in autumn (Table 1.7, Figure 1.14).

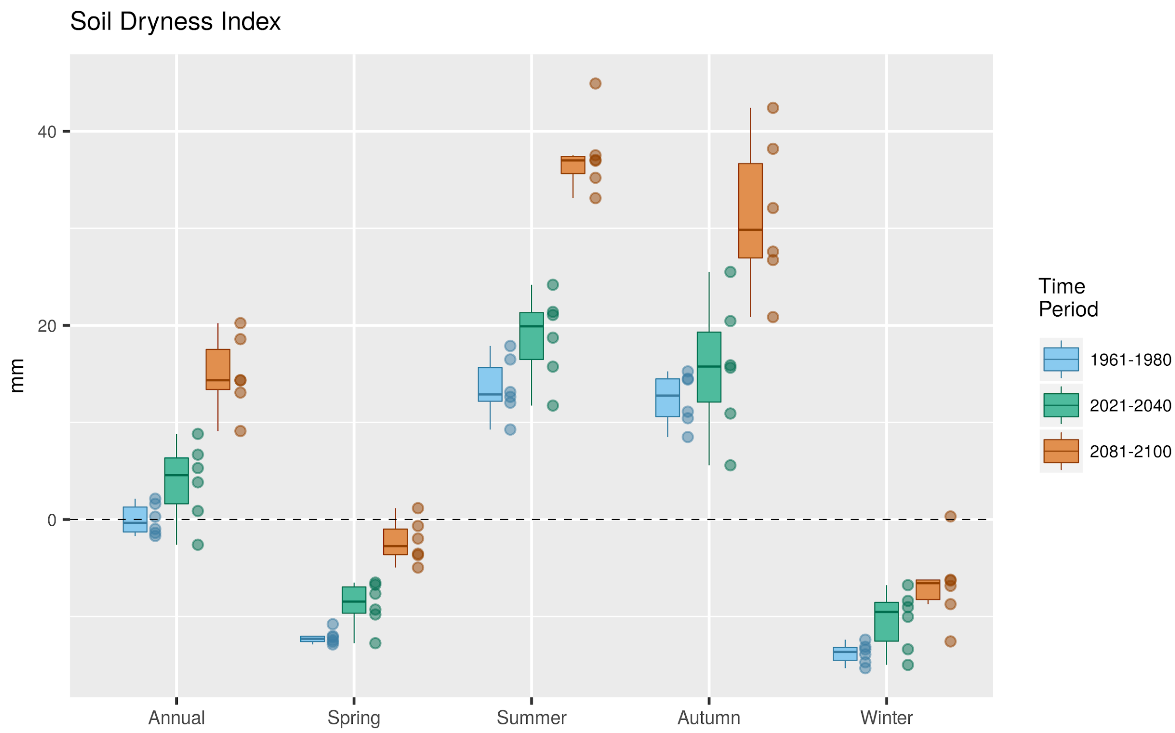


Figure 1.12: Six-model summary of changes in monthly soil dryness index averaged over Tasmania under the A2 emission scenario for each season in the baseline (1961-1980), near future (2021-2040) and end of century periods (2081-2100). Values represent change from the multi-model mean annual value for the baseline period. The box indicates the multi-model range, the bar shows the mean, and ticks indicate the mean for each of the six downscaled climate models.

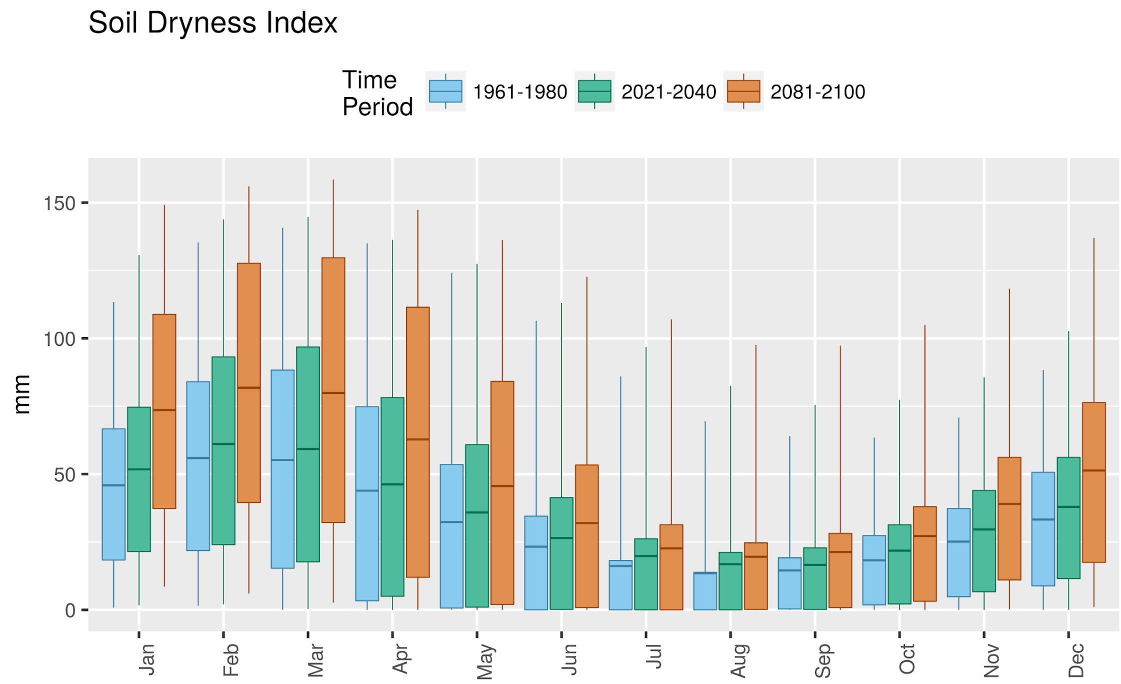


Figure 1.13: Annual cycle of soil dryness index projected by the six climate models for the baseline (1961-1980), near future (2021-2040) and end of century (2081-2100) periods. The box indicates the interquartile range, the bar shows the mean, and the whiskers extend from the 5th to the 95th percentile.

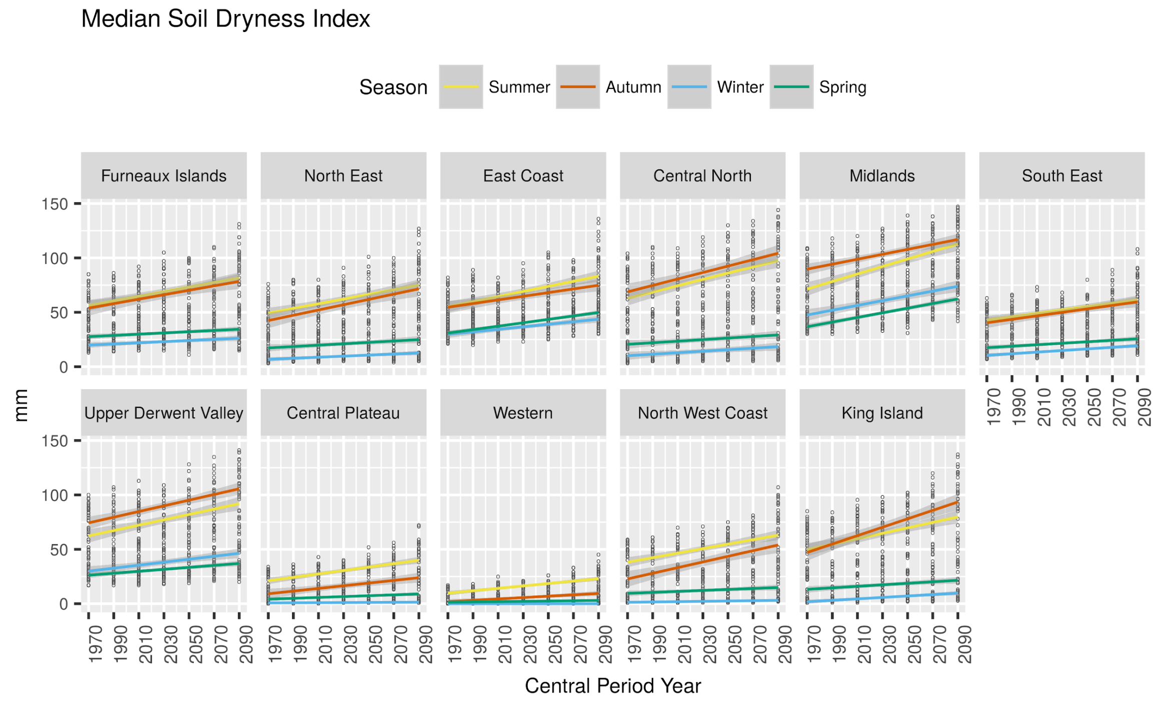


Figure 1.14: Trends in seasonal soil dryness index projected by the six climate models in 20-year periods from 1961 to 2100 in each of the BoM forecast districts. Black dots represent one value for each of the six models in each season. The grey shadow represents the weighted mean square error of the regression.

Table 1.7: Rate of change (per year) in Soil Dryness Index in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.14.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	0.202	0.164	0.056	0.064
North East	0.205	0.198	0.059	0.071
East Coast	0.205	0.129	0.114	0.166
Central North	0.240	0.218	0.073	0.076
Midlands	0.263	0.164	0.162	0.212
South East	0.157	0.137	0.073	0.087
Upper Derwent Valley	0.209	0.169	0.116	0.114
Central Plateau	0.165	0.152	0.064	0.068
Western	0.110	0.079	0.003	0.016
North West Coast	0.208	0.241	0.038	0.049
King Island	0.242	0.330	0.081	0.069

1.3.5 Relative Humidity

Monthly minimum relative humidity is projected to decrease in spring and summer by the end of the century, with little change evident in autumn and winter (Figure 1.15). When averaged across Tasmania, there is little change projected to occur in relative humidity in any month of the year (Figure 1.16).

In the Central Plateau, East coast, Midlands and North East districts, there is a slight decrease in minimum relative humidity by the end of the century during the spring months (Figure 1.18). The remaining districts show slight increases in some months and slight decreases in others. Slight decreases are also projected during the autumn months in the Central Plateau, Furneaux, King Island, North East, North West, Upper Derwent and Western districts (Table 1.8, Appendix A).

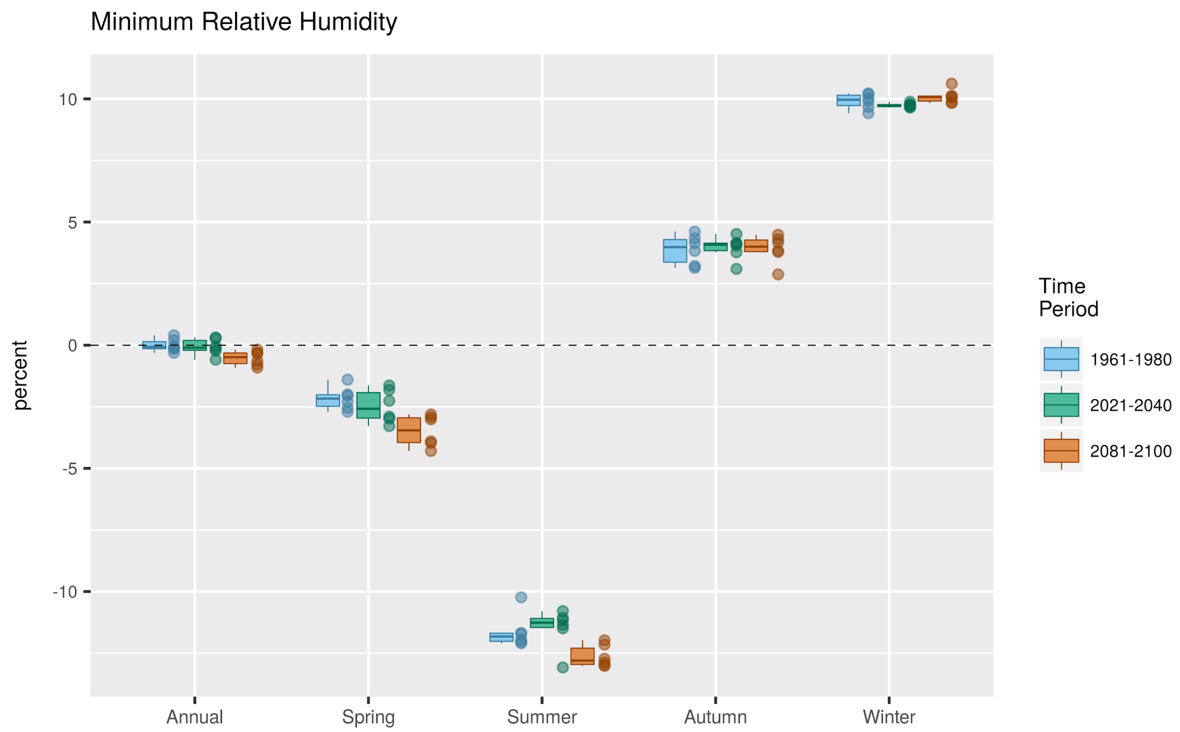


Figure 1.15: Six-model summary of changes in monthly minimum humidity averaged over Tasmania under the A2 emission scenario for each season in the baseline (1961-1980), near future (2021-2040) and end of century periods (2081-2100). Values represent change from the multi-model mean annual value for the baseline period. The box indicates the multi-model range, the bar shows the mean, and ticks indicate the mean for each of the six downscaled climate models.

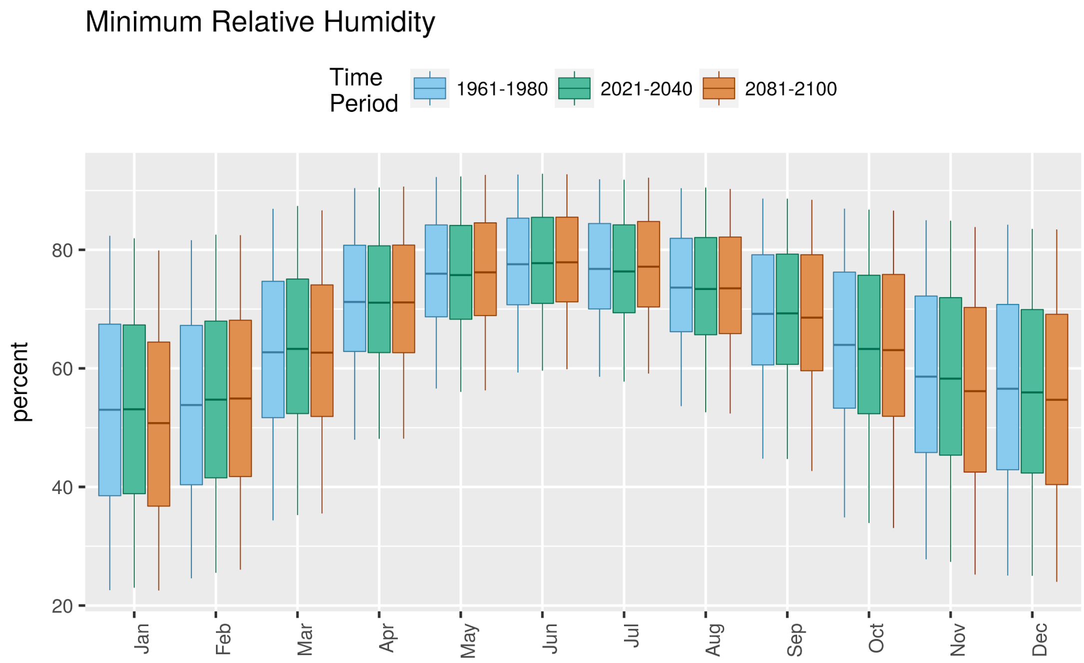


Figure 1.16: Annual cycle of minimum relative humidity projected by the six climate models for the baseline (1961-1980), near future (2021-2040) and end of century (2081-2100) periods. The box indicates the interquartile range, the bar shows the mean, and the whiskers extend from the 5th to the 95th percentile.

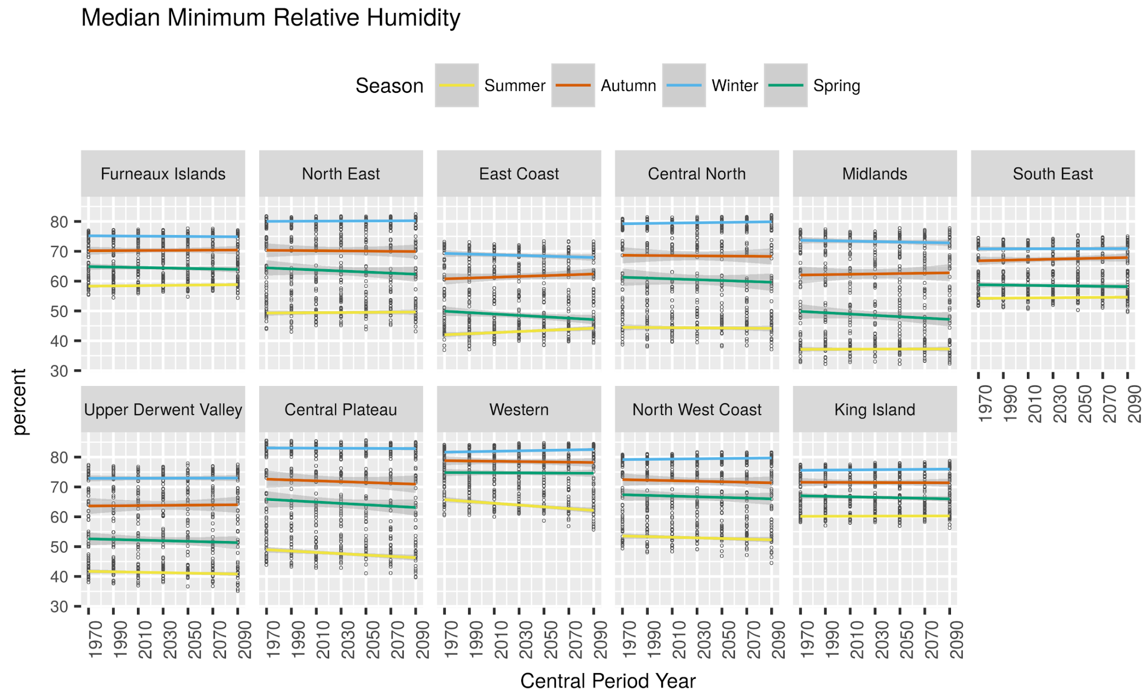


Figure 1.17: Trends in seasonal minimum relative humidity projected by the six climate models in 20-year periods from 1961 to 2100 in each of the BoM forecast districts. Black dots represent one value for each of the six models in each season. The grey shadow represents the weighted mean square error of the regression.

Table 1.8: Rate of change in Minimum Relative Humidity in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.17.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	0.008	0.003	-0.002	-0.008
North East	0.004	-0.002	0.001	-0.018
East Coast	0.017	0.012	-0.010	-0.021
Central North	-0.001	-0.002	0.005	-0.013
Midlands	0.004	0.006	-0.007	-0.020
South East	0.005	0.009	0.000	-0.006
Upper Derwent Valley	-0.002	0.005	-0.000	-0.009
Central Plateau	-0.019	-0.011	-0.002	-0.020
Western	-0.023	-0.003	0.009	-0.002
North West Coast	-0.008	-0.008	0.005	-0.011
King Island	0.005	-0.000	0.004	-0.009

1.3.6 Fire Danger Indices (FFDI, MFDI)

Substantial increases in annual values of the fire danger indices (FFDI, MFDI) are projected to occur across Tasmania by the end of the century (Figure 1.18). However, the extent to which the indices change across the seasons differs slightly, reflecting the different emphasis on soil dryness and antecedent rainfall in each index. In the near term, increases in the Forest Fire Danger Index are projected by all climate models, for all seasons except autumn. In contrast, the mean Moorland Forest Danger Index increases in spring and winter by the 2021-2040 period and decreases in autumn and summer.

By the end of the century, increases in FFDI are projected for all seasons, with very dramatic increases in spring and summer. The MFDI increases substantially in spring and winter, while the mean MFDI declines slightly in autumn. Changes to the extremes of both indices are also evident, with the 95^{th} percentiles being substantially higher by the end of the century for the months from October to May (FFDI), and August to October (MFDI).

The projected increases in FFDI are lowest during the months April to September, while the MFDI declines slightly or remains similar to current values from February to May (Figure 1.19). In the warmer months, there is a shift in FFDI so that by the end of the century, November FFDI is higher than what is currently experienced in December, and future January FFDI values exceed any currently experienced in any month. The MFDI shows a consistent shift in fire danger indicating higher fire danger values earlier in the year. From June through to

December, monthly MFDI by mid-century exceeds the current value for the following (warmer) month. By the end of the century the differences are greatest in late winter and spring.

The Midlands and East Coast districts are projected to have the fastest rate of increase in FFDI in spring, while increases in autumn are fastest in the North West Coast, Central North and Central Plateau districts (Table 1.9, Figure 1.20). Rates of change in the MFDI are more uniform across the districts in all seasons (Table 1.10).

The FFDI and MFDI are not equally important across all forecast districts. The MFDI was developed to better represent fire danger in Buttongrass Moorlands, where soil dryness is less important in determining fire danger than in forests. It is also the most appropriate of the two indices for heathland vegetation types. The relevance of each fire danger index will therefore differ depending on the predominant vegetation in each district.

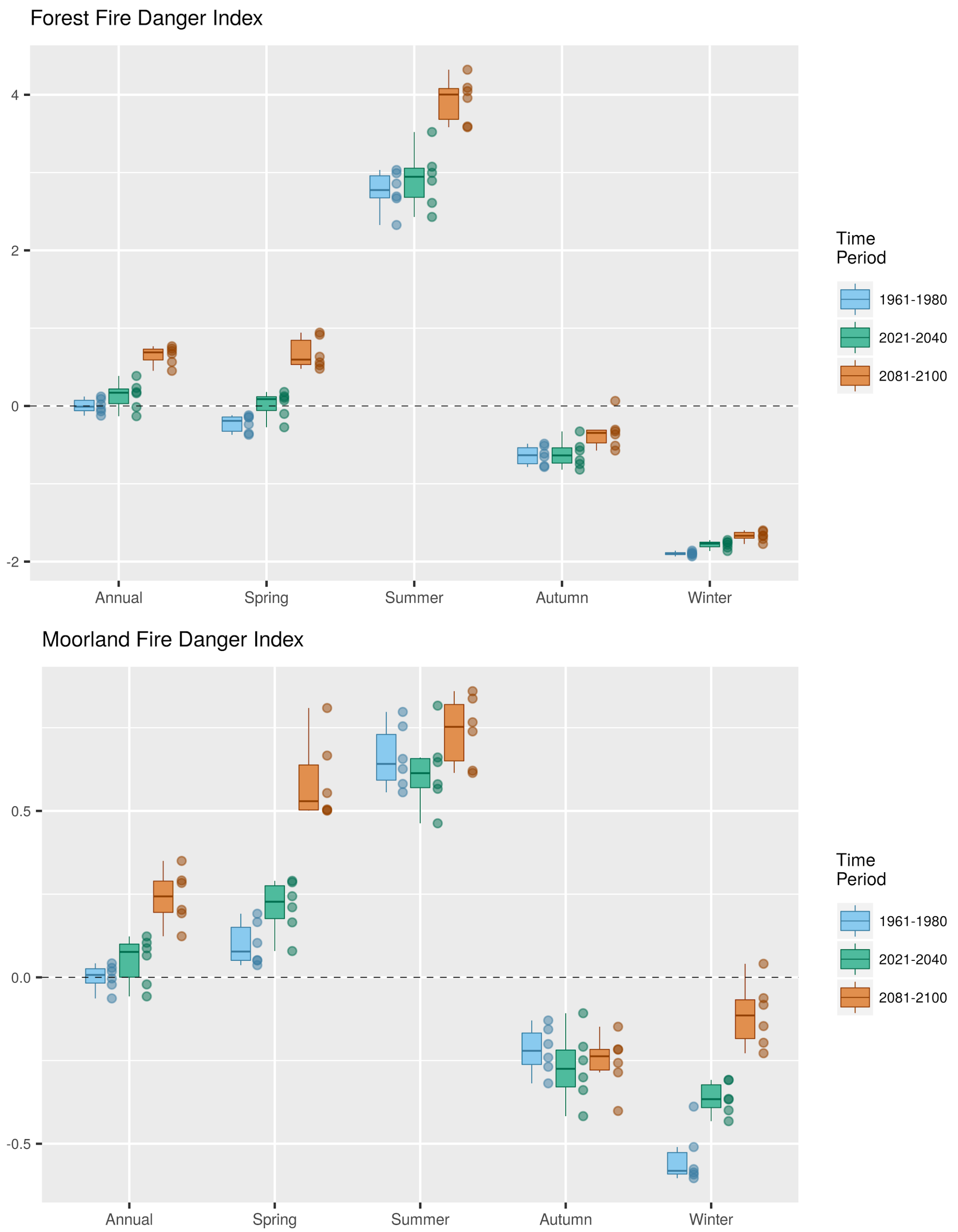


Figure 1.18: Six-model summary of changes in fire danger indices, FFDI and MFDI, averaged over Tasmania under the A2 emission scenario for each season in the baseline (1961-1980), near future (2021-2040) and end of century periods (2081-2100). Values represent change from the multi-model mean annual value for the baseline period. The box indicates the multi-model range, the bar shows the mean, and ticks indicate the mean for each of the six downscaled climate models.

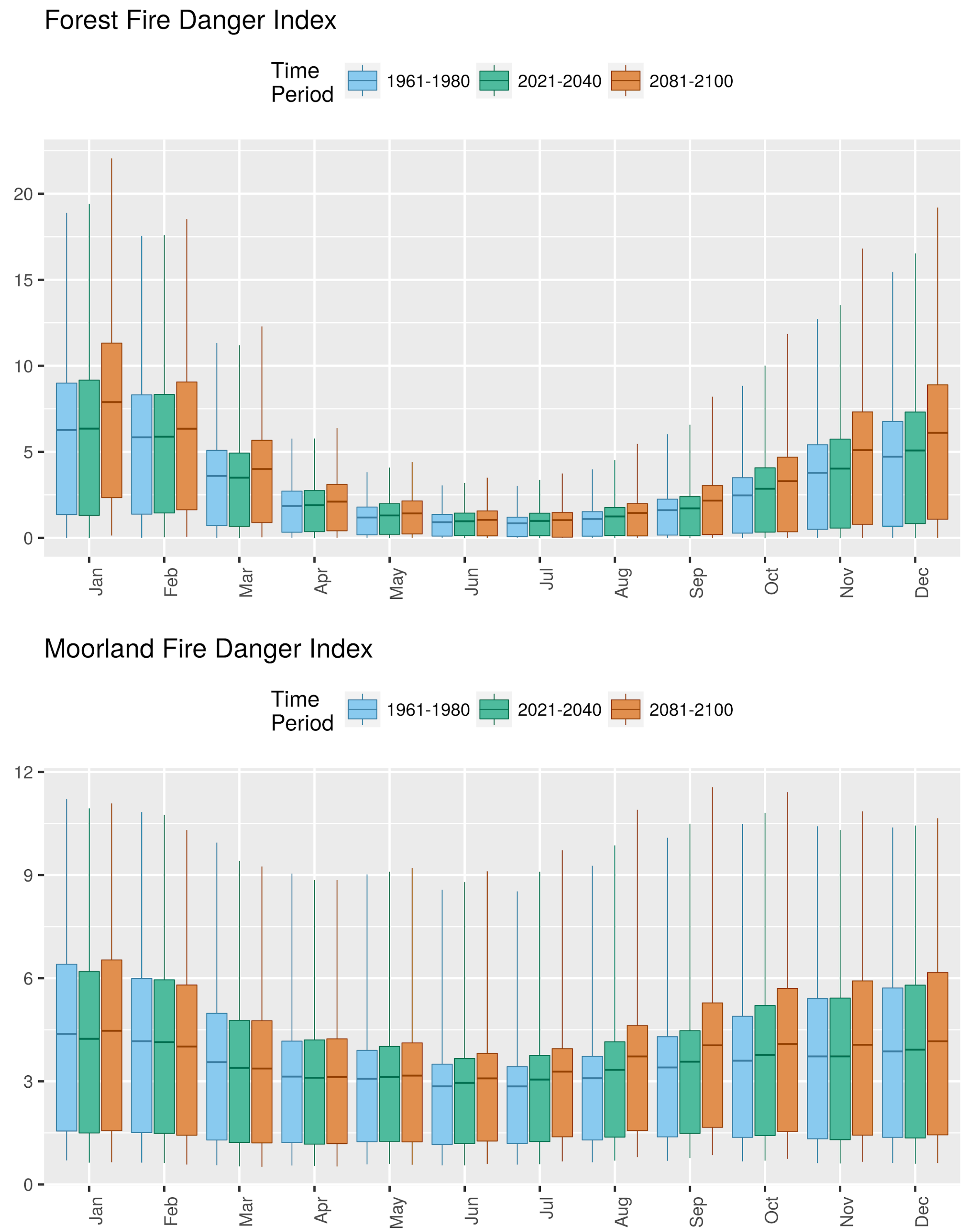
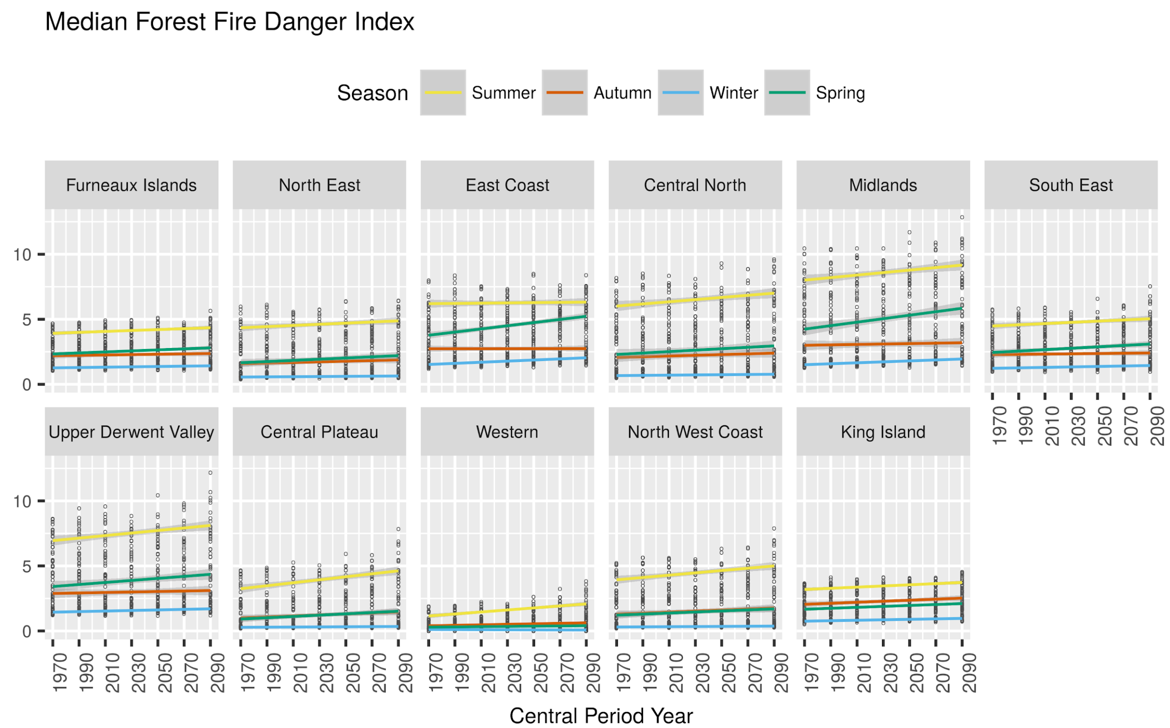


Figure 1.19: Annual cycle of monthly fire danger indices (FFDI, MFDI) projected by the six climate models for the baseline (1961-1980), near future (2021-2040) and end of century (2081-2100) periods. The box indicates the interquartile range, the bar shows the mean, and the whiskers extend from the 5th to the 95th percentile.



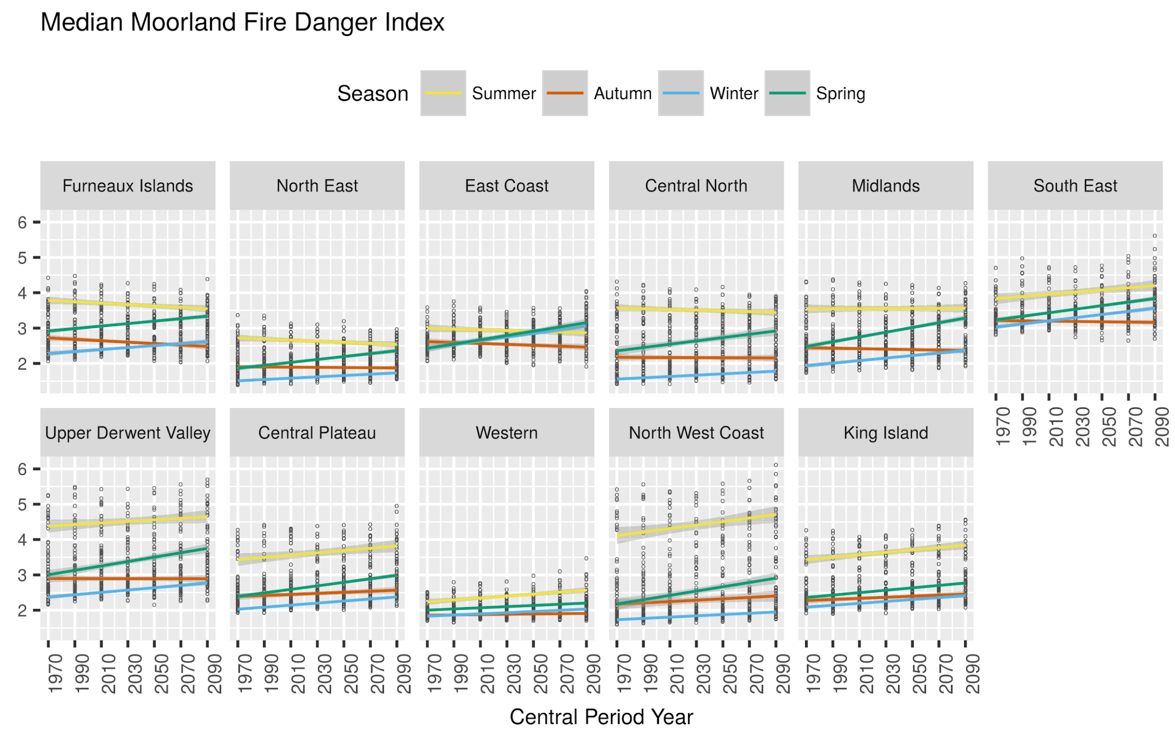


Figure 1.20: Trends in seasonal fire danger indices, FFDI and MFDI, projected by the six climate models in 20-year periods from 1961 to 2100 in each of the BoM forecast districts. Black dots represent one value for each of the six models in each season. The grey shadow represents the weighted mean square error of the regression.

Table 1.9: Rate of change (per year) in Forest Fire Danger Index in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.20.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	0.003	0.002	0.002	0.005
North East	0.005	0.003	0.001	0.007
East Coast	0.002	0.000	0.005	0.013
Central North	0.010	0.004	0.001	0.007
Midlands	0.009	0.002	0.004	0.015
South East	0.005	0.001	0.003	0.008
Upper Derwent Valley	0.009	0.002	0.003	0.010
Central Plateau	0.012	0.004	0.002	0.008
Western	0.010	0.003	-0.000	0.002
North West Coast	0.010	0.005	0.001	0.006
King Island	0.005	0.004	0.003	0.004

Table 1.10: Rate of change in Moorland Fire Danger Index in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.20.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	-0.002	-0.002	0.004	0.004
North East	-0.002	-0.001	0.003	0.004
East Coast	-0.002	-0.002	0.006	0.005
Central North	-0.001	-0.001	0.003	0.004
Midlands	-0.001	-0.001	0.004	0.005
South East	-0.000	-0.001	0.006	0.005
Upper Derwent Valley	-0.001	-0.001	0.005	0.005
Central Plateau	-0.000	0.001	0.004	0.005
Western	0.002	0.001	0.002	0.002
North West Coast	0.002	0.001	0.002	0.004
King Island	0.002	0.002	0.004	0.004

1.3.7 Wind Speed and Direction

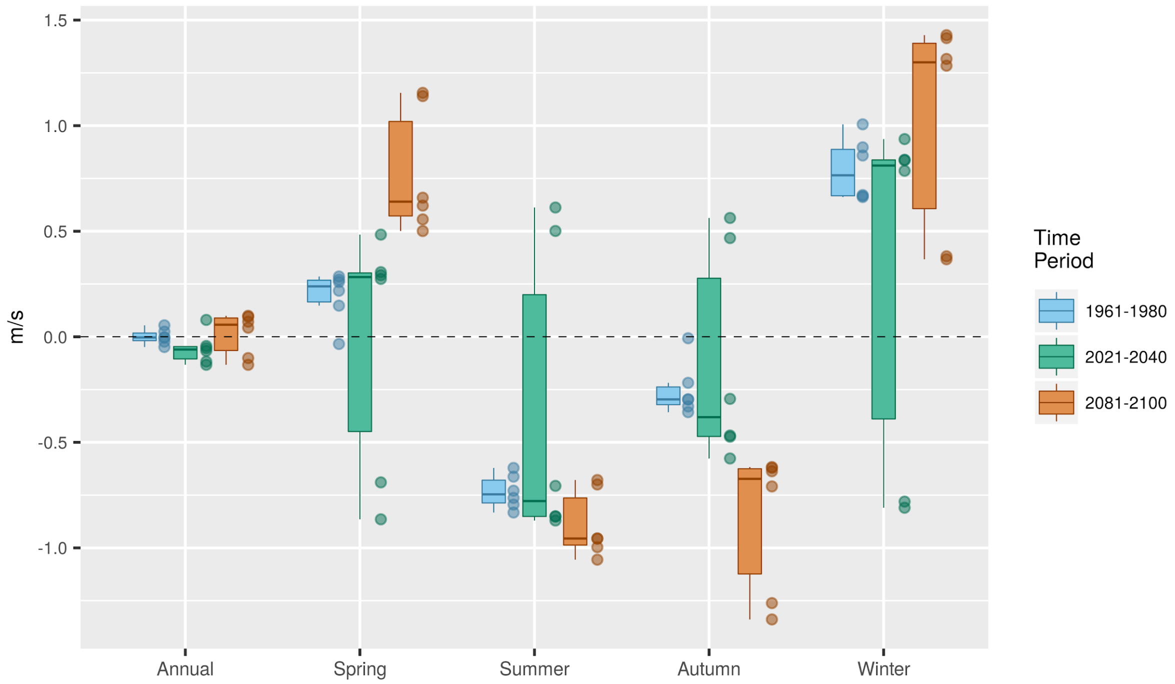
The projections of wind speed for the near-term period are highly variable, with a large range in wind speed across the climate models (Figure 1.21). By the end of the century that very large range is reduced but remains more variable than in the baseline period. An increase in variability in wind in the future is consistent with the poleward shift and increase in intensity of the sub-tropical ridge that is projected to occur (Grose et al. 2015c).

The wind output from the model has not been validated against observations and appears to underestimate wind speed. This would contribute to the conservative estimates for FFDI and MFDI, since wind is a component in those calculations. The MFDI is more sensitivity to wind speed than FFDI, so larger magnitude changes may be expected in this index. For this reason, we only consider the relative differences between time periods in these variables.

By the end of the century, increased maximum daily winds are projected across Tasmania for spring, and decreased daily winds are projected to occur in autumn. Reductions in maximum daily wind speed are projected for May and June by the end of the century (Figure 1.22). From July through to November, maximum daily wind speed increases. Similar trends in wind speed are projected for all districts (Figure 1.24). Maximum daily wind speeds are projected to decrease in autumn, increase in spring, although the rates of change are low (Table 1.11). Little or no change in maximum daily wind speed is projected in summer and winter.

Changes in wind direction are projected (Figure 1.21), but these changes represent only a slight change when averaged over Tasmania (Figure 1.23). However, rates of change are higher within some districts, with the Furneaux, North East and East Coast districts showing the greatest rates of change in autumn and summer (Figure 1.23, Table 1.12).

Maximum Daily Wind Speed



Dominant Daily Wind Direction

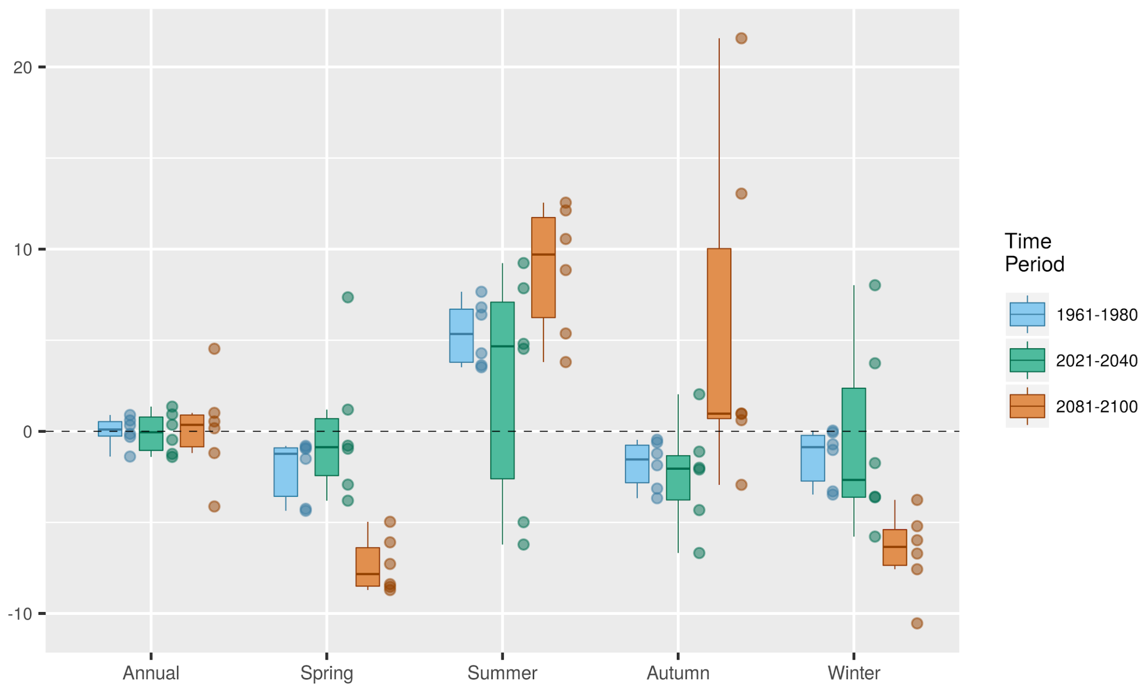


Figure 1.21: Six-model summary of changes in maximum daily wind speed and dominant wind direction across Tasmania under the A2 emission scenario for each season in the baseline (1961-1980), near future (2021-2040) and end of century periods (2081-2100). Values represent change from the multi-model mean annual value for the baseline period. The box indicates the multi-model range, the bar shows the mean, and ticks indicate the mean for each of the six downscaled climate models.

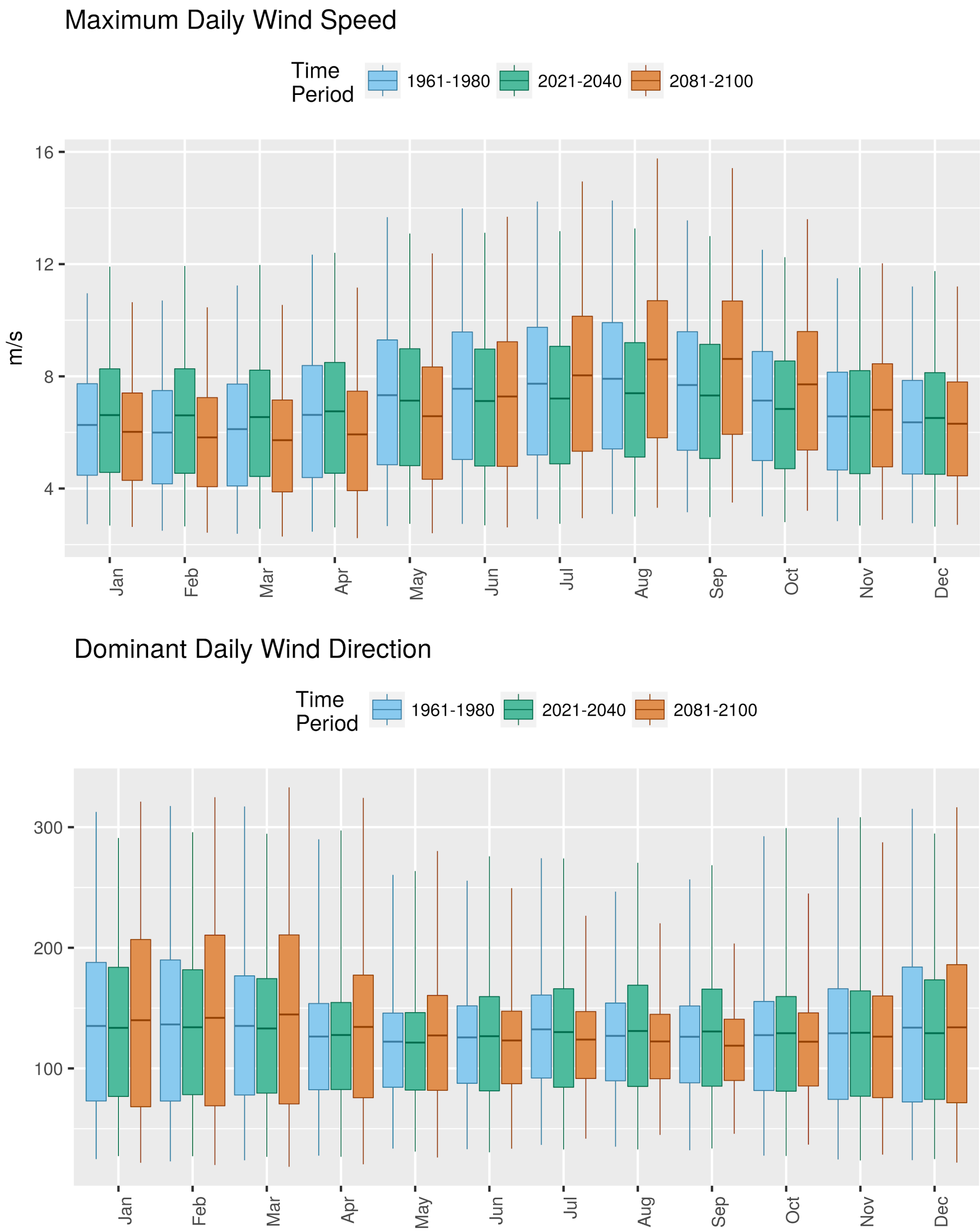


Figure 1.22: Annual cycle of maximum daily wind speed and dominant daily wind direction projected by the six climate models for the baseline (1961-1980), near future (2021-2040) and end of century (2081-2100) periods. Wind direction is shown as degrees clockwise from North. The box indicates the interquartile range, the bar shows the mean, and the whiskers extend from the 5th to the 95th percentile.

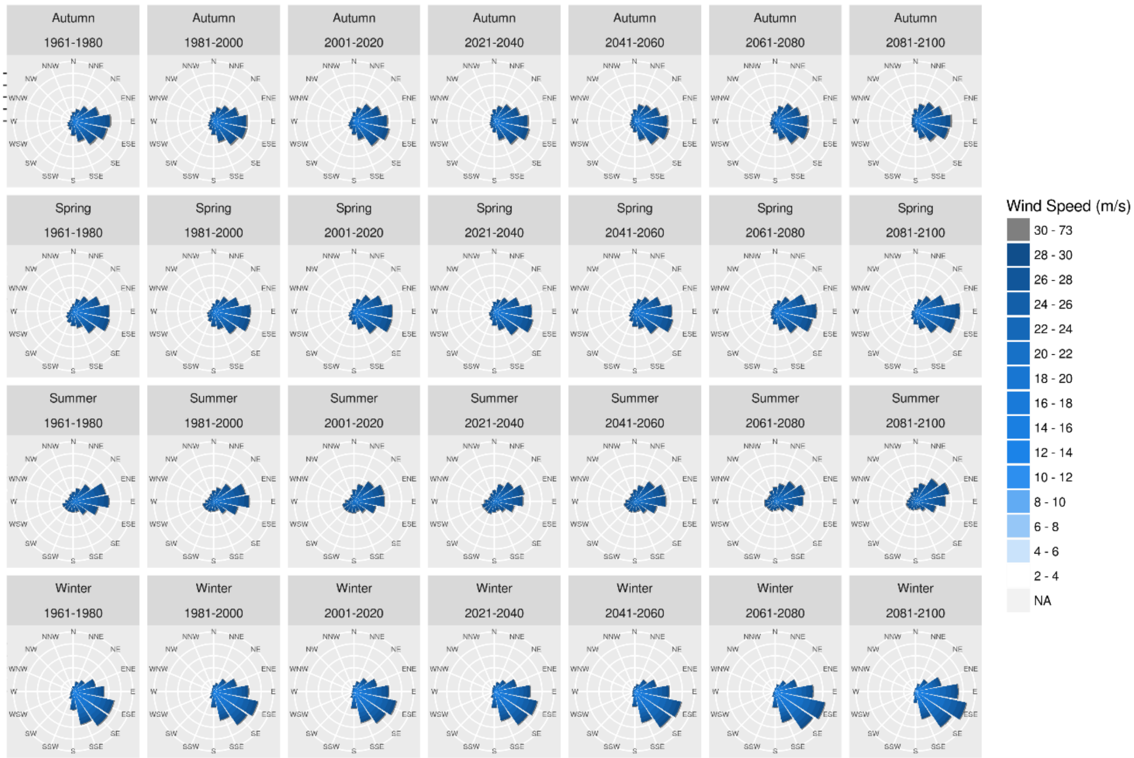
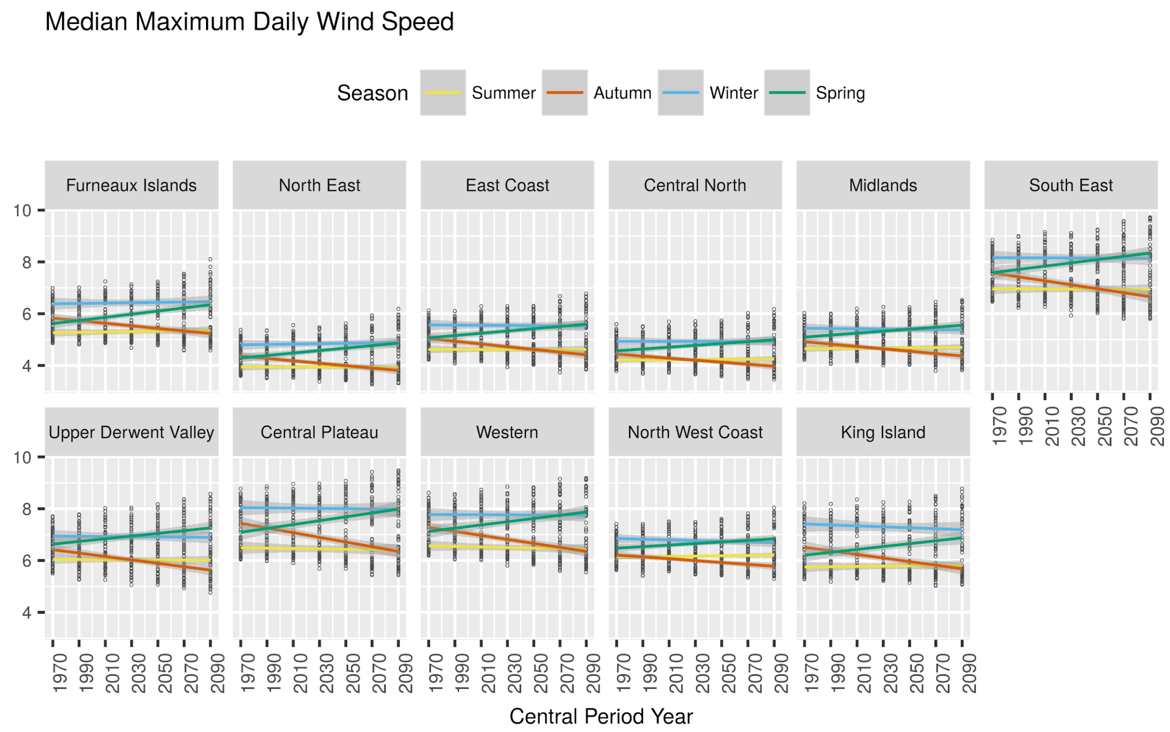


Figure 1.23: Maximum daily wind speed and wind direction across Tasmania in each season within twenty year periods, from the baseline (1961-1980) to the end of the century (2081-2100).



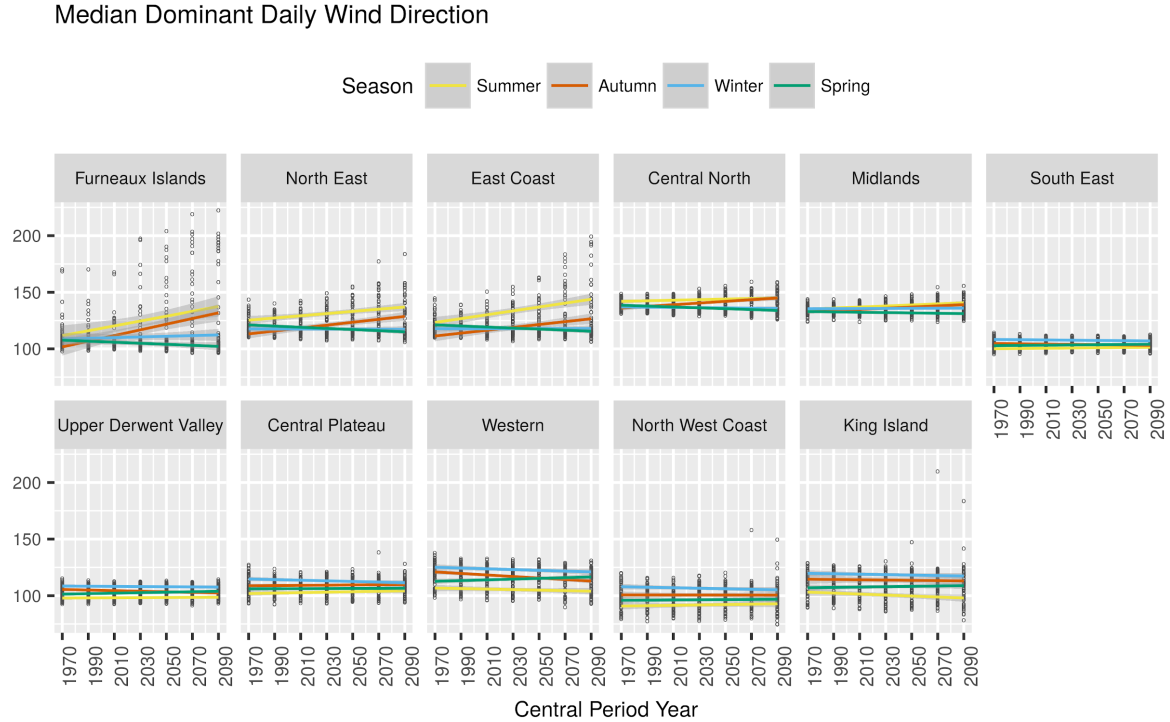


Figure 1.24: Trends in seasonal maximum daily wind speed and dominant daily wind direction projected by the six climate models in 20-year periods from 1961 to 2100 in each of the BoM forecast districts. Wind direction is shown as degrees clockwise from North. Black dots represent one value for each of the six models in each season. The grey shadow represents the weighted mean square error of the regression.

Table 1.11: Rate of change (per year) in Maximum Daily Wind Speed in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.24.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	0.001	-0.005	0.002	0.008
North East	-0.000	-0.005	0.001	0.005
East Coast	0.000	-0.005	0.000	0.005
Central North	0.000	-0.004	0.000	0.004
Midlands	0.000	-0.004	-0.000	0.004
South East	-0.000	-0.008	0.001	0.007
Upper Derwent Valley	-0.000	-0.006	0.000	0.005
Central Plateau	-0.000	-0.008	0.000	0.007
Western	-0.001	-0.007	0.000	0.007
North West Coast	0.001	-0.004	-0.001	0.004
King Island	0.000	-0.007	-0.001	0.006

Table 1.12: Rate of change (per year) in Dominant Daily Wind Direction in each season. Values are the slope of the linear least squares regression fit to the twenty-year mean seasonal values for the six climate models as shown in Fig. 1.24.

region	Summer	Autumn	Winter	Spring
Furneaux Islands	0.044	0.172	-0.003	-0.149
North East	0.059	0.161	-0.009	-0.116
East Coast	0.064	0.145	-0.007	-0.121
Central North	0.044	0.123	-0.007	-0.061
Midlands	0.065	0.111	0.009	-0.058
South East	0.055	0.097	-0.021	-0.084
Upper Derwent Valley	0.061	0.087	-0.011	-0.057
Central Plateau	0.030	0.036	-0.024	-0.028
Western	0.002	-0.016	-0.027	0.004
North West Coast	0.020	0.046	-0.021	-0.042
King Island	-0.006	0.087	0.005	-0.060

1.4 Discussion – Implications for prescribed burning as a management tool in the future

The current operational guidelines for planned burning in Tasmania specify the weather conditions under which burning can be applied in different vegetation types (Marsden-Smedley, 2009; Table 1.14). Currently, these conditions generally occur in autumn in Tasmania, so the majority of prescribed burning is carried out in this season (with some burning in spring).

Substantial increases in fuel availability (indicated by the Drought Factor) and decreases in fuel moisture (Soil Dryness Index (SDI)) are projected, with very strong drying trends projected for autumn and spring by the end of the century. This suggests that the flammability of different vegetation types will increase in these seasons, reducing the ability to safely conduct and contain prescribed burns. These trends become evident in the near future (2021-2040) and represent substantial changes relative to the past by the end of the century (2081-2100).

There is variability in the rate of change projected across the BoM forecast districts, but overall, the trends are similar across all of districts in Tasmania. Wind speed and direction are not projected to change substantially in autumn and spring, but increased temperatures are projected to occur across Tasmania (up to 2.7°C by the end of century under the high emissions scenario). In some districts reduced rainfall in these seasons is also projected. Substantial increases in Soil Dryness Index are projected to occur across Tasmania in the future, and change is projected to occur rapidly over the next decades. In the near term (2021-2040), all models project an increase in soil dryness index in summer, and there is high model agreement that there will be increased soil drying during spring and winter. By the end of the century, substantial increases in the Soil Dryness Index are projected by all climate models in all seasons. The fastest rate of soil drying is projected for King Island, North West Coast and Central North districts in autumn, and in the Midlands and East Coast districts in spring.

By the end of the century, very large increases in both FFDI and MFDI are projected for spring. The FFDI also increases dramatically in summer (discussed in detail in Fox-Hughes et al. 2014), while the MFDI increases substantially in winter. These changes have important implications for the ability to apply prescribed burns in spring and winter to mitigate the increased fire danger that is projected to occur in summer. Over time, the burning period may move towards the winter and early spring months, as opportunities for safe burning decline in the autumn months.

Although there is higher uncertainty in the projections of rainfall, seasonal trends are evident in several districts. In the Central Plateau, King Island, North West, and Midlands districts there is high model agreement projecting decreased rainfall in all spring months by the end of the century. In the East Coast, declines in September and October are projected by most models. There is also high model agreement for substantial reductions in autumn rainfall in the Western district. The Central Plateau is projected to experience the fastest decline in autumn and Spring rainfall, while other districts, such as the East Coast, Upper Derwent and South East districts, have little change projected for these seasons.

The results presented in this report may be conservative estimates of the drying trends in spring. A recent comparison of the Climate Futures for Tasmania projections with other available climate models found that the CFT projections "are at the wetter end of the plausible range of spring rainfall projections" (Grose et al. 2015a, pg 28). The CFT results show little trend in spring rainfall across Tasmania, while other models project a decrease in spring rainfall. An overestimate of spring rainfall would lead to underestimates of the Drought Factor and Soil Dryness Index in spring.

As the frequency of warmer and drier conditions increases in autumn and spring across Tasmania, the likelihood of all variables coinciding at their maximum values (e.g. maximum wind speed, lowest relative humidity, highest Soil Dryness Index and Drought Factor) can be expected to increase. This increases the likelihood that fires will burn with faster rates of spread, higher intensities and a higher risk of escape than under current conditions (Marsden-Smedley 2009). This higher risk will constrain the application of prescribed burning in the autumn months, when the majority of prescribed burns are currently carried out, and the burning period may move to the winter and early spring months. In this report, we have considered each variable in isolation. Further research into how frequently suitable conditions for prescribed burning coincide in the projections is necessary to identify safe windows of opportunity.

The results suggest that there will be a narrower window of suitable conditions for burning in autumn in the future, driven by changes in temperature and the drying trend, which is reflected in increased soil dryness index and drought factor. This has important consequences for the ability to manage bushfire risk using prescribed burning in the coming decades. Fire managers will need to reconsider the timing and resourcing of prescribed burning and build capacity to mobilise rapidly when weather conditions are suitable during autumn and winter. Additionally, other tools for reducing fuel loads may need to be considered, such as mechanical removal of fuels and the maintenance of fire breaks by grazing. Research into the impacts of such approaches is still needed. Prescribed burning will always play an important role in fire management, but it is likely that it will need to be supplemented by other fuel reduction techniques under future climate conditions.

Table 1.13: Operational guidelines for planned burning in different vegetation types in Tasmania, from Marsden-Smedley (2009). Guidelines prescribe wind speeds at 10m for forest and at 1.7-2m for other vegetation types. Wind speeds of <20 km/h is recommended for sites with secure boundaries, otherwise 10 km/hr is more appropriate. Values of the fire danger index are the appropriate index for the vegetation type (FFDI – forest; scrub fire danger – Heathland, scrub and gorse; grassland fire danger – native grassland; MFDI - Buttongrass moorland). Fire frequency for ecological management is different, and specified in management plans. * wet scrub only

	Temperature (°C)	SDI	Relative humidity (%)	Wind speed (km/h)[1]	Fire Danger Index	Fire frequency (years) (asset protection)
Dry eucalypt forest	**10-25**	**<125**	**40-80**	**≤30**	**5-10**	**4-10**
Heathland, dry scrub, wet scrub	**10-25**	**15 – 25 ***	**40-80**	**5-20**	**<20**	**5-10**
Buttongrass moorland	**10-25**	**≤10**	**40-90**	**≤20**	**≤10**	**5-10**
Native grassland	**10-25**	**-**	**40-80**	**≤20**	**≤5**	**-**
Gorse (flammable weeds)	**10-25**	**≤20**	**50-85**	**≤20**	**≤10**	

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Part 2 - Synoptic weather patterns conducive to fire in Tasmania

2.1 Introduction

The recent Future Fire Danger project using Climate Futures for Tasmania (CFT) data highlighted changing fire danger through the twenty-first century and examined synoptic weather patterns associated with high fire danger in a number of areas of Tasmania (Fox-Hughes et al. 2014; Fox–Hughes et al. 2015). The project demonstrated that, by the end of the current century, there was a projected increase in the number of days of elevated fire danger associated with each region's typical "bad day" synoptic pattern. However, the change in frequency of these synoptic patterns over Tasmania remained unknown.

Synoptic surface pressure patterns summarise the weather conditions likely to be experienced over their domains. For fire managers in Tasmania, such patterns provide an indication of which areas might be suitable for fuel reduction burning at different times of the year, or which may require supplementation of fire suppression resources. There is a clear interest in knowing whether there will be a change in the frequency of particular synoptic patterns in the future. In general, warmer season north to north-westerly winds are associated with the worst fire danger experienced in Tasmania, which includes a high degree of atmospheric instability. The northwest Tasmanian fires that occurred during the 2015-16 summer were characterised by persistent easterly and north-easterly winds that were offshore and therefore drier than usual over most of the fire grounds. The prospect of such conditions becoming more common is of considerable interest to fire and land managers tasked with managing bushfire risk in Tasmania. Knowing whether the frequency of such conditions is likely to change over coming decades will be an important consideration for fire managers, potentially affecting the size of windows of opportunity available to conduct management burns.

2.2 Method

To gauge the likelihood of changes in the frequency of typical synoptic patterns over Tasmania, pressure gradient information was derived from the daily surface pressure fields available from the CFT high resolution models. The locations of the points sampled to derive synoptic patterns are shown as blue dots in Figure 2.1. Pressure gradients obtained from these samples were classified into compass direction, and further classified according to the strength of the pressure gradient (and, therefore of the winds over Tasmania). For example, occasions on which the difference between the top right and bottom left points exceeded the differences between other pairs of corner points were classified as north-westerly streams. If the pressure gradient exceeded 8 hPa, the stream was classified as a strong north-westerly stream.

In addition, two other classifications were used: one corresponding to anticyclonic conditions (when the pressure was higher over the central pressure sample point than over surrounding points) and the other corresponding to cyclonic conditions (with lower pressure over Tasmania than its surroundings). For each synoptic type, plots were generated of the change in the annual number of occurrences of that type through time, for each CFT model. A multimodel mean of the annual count was calculated for each type, together with a 30 year running mean of the multimodel annual count of occurrences of that type.

It should be noted that the typing used above could be varied slightly. One could choose a low, positive but non-zero, pressure difference across Tasmania below which the stream was classified as “Anticyclonic”, for example, to reflect the fact that a synoptic pattern could reasonably be regarded as anticyclonically dominated despite there being a small pressure gradient across the island. The scheme used was chosen as being simple and clear. The criterion for a “strong” stream was used as it approximated the system used for many years in Tasmanian fire weather forecasting to identify situations in which seabreezes would be excluded from forming on lee coasts, thereby increasing fire dangers experienced in those areas (Marsh 1987).

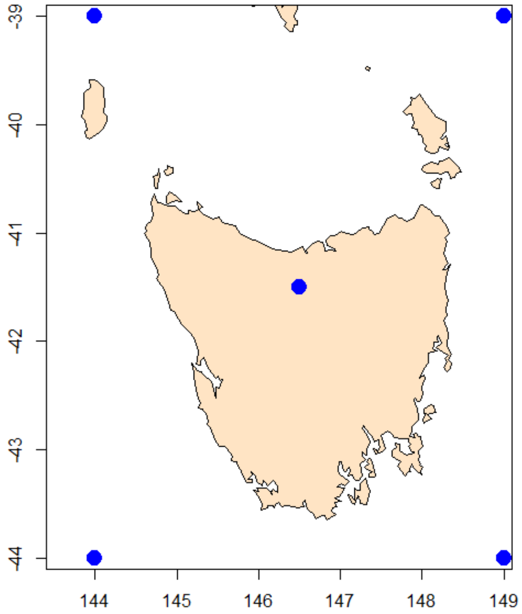


Figure 2.1: Location of pressure sample points used to derive synoptic patterns over Tasmania.

In Figure 2.2, annual counts of each model are displayed as thin lines, the multimodel mean of annual count is the bold red line, and the 30 year running mean of the multimodel mean is the black dashed line. The figure shows clearly a considerable interannual variation, and variation between models, of the count of north-easterly conditions over Tasmania (ie with lower pressure to the northwest of the state and higher pressure to the southeast). There is a suggestion of a slight increase in the number of days of such north-easterly flow during the current century, but it is not a strong trend. Overall, initial analysis suggests that there are no strong trends within any of the synoptic types on an annual basis. The complete set of annual plots is displayed in Figure 2.3. Note that the y-axis scale varies between plots to best display the data.

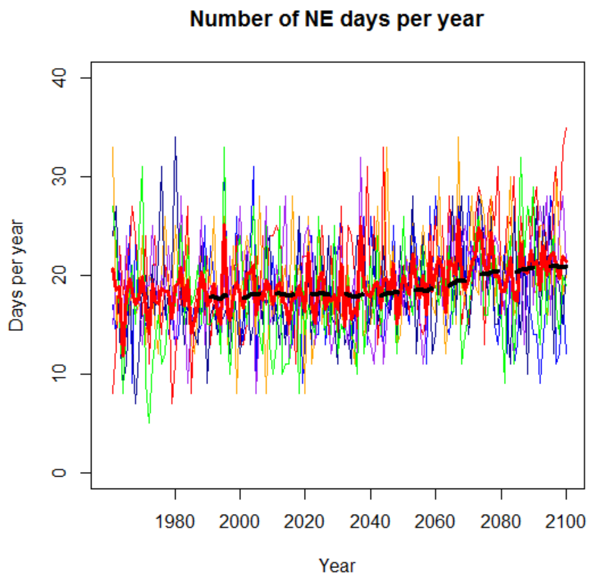
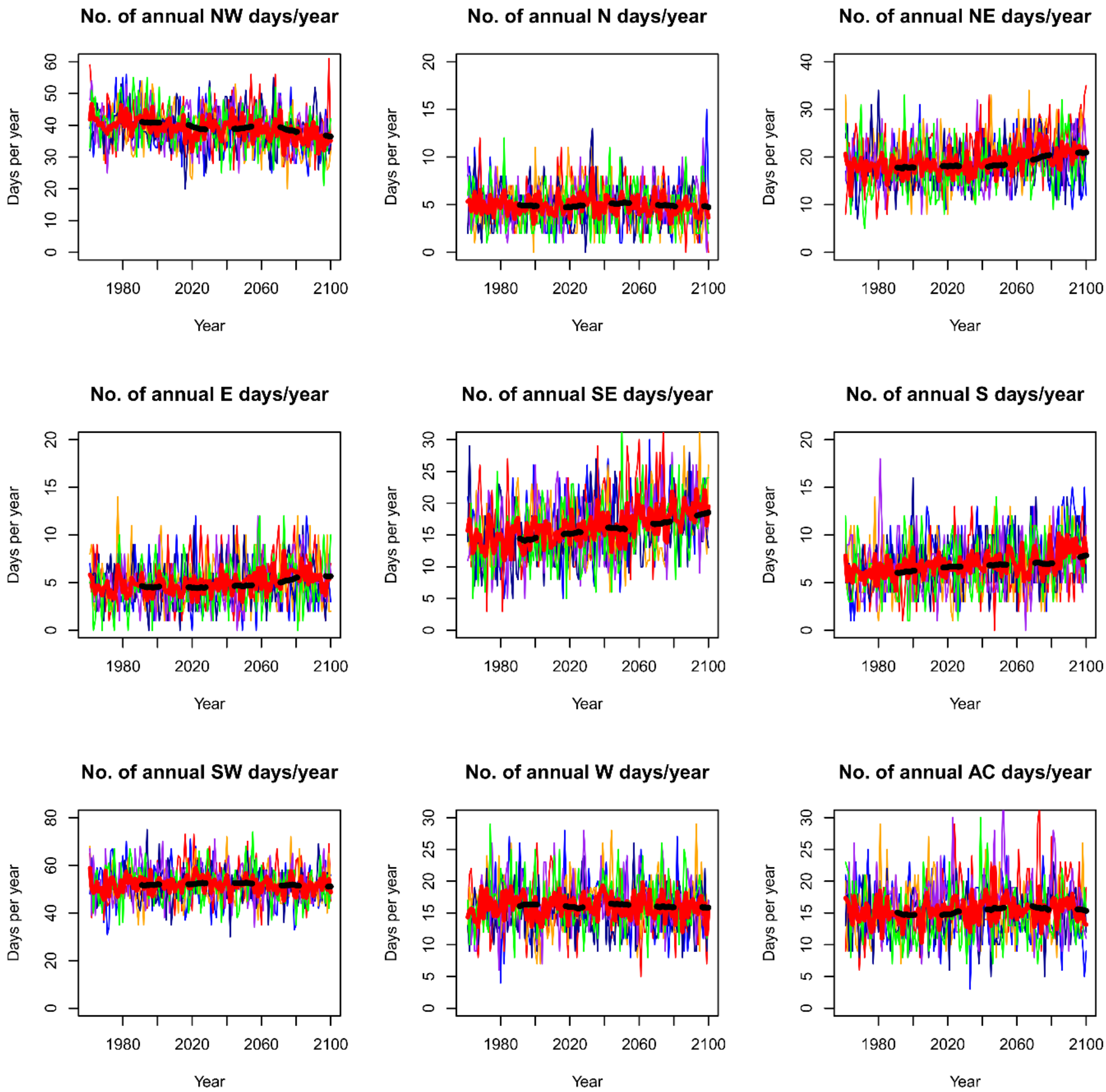


Figure 2.2: Multi-model plot of days per year on which north-easterly conditions occur. Annual counts of each model are displayed as thin lines, the multimodel mean of the annual count is the bold red line, and the 30 year running mean of the multimodel mean is the black dashed line.

The breakdown of synoptic type by season is displayed in Figures 2.4 to 2.7. Little change is projected in the multi-model mean for winter or spring. In summer, however, and to a generally smaller extent in autumn, there is evidence of a trend through the current century for an increase in easterly quarter types, and a decrease in westerly types, including the strong NW, W and SW streams. Consequently, the small and fairly gradual changes projected in the frequencies of synoptic types over Tasmania are not likely to affect prescribed burning opportunities during the spring and autumn, in particular.

It is quite likely (but hasn't been confirmed in this work) that the trends identified above are a consequence of the southward movement of the subtropical ridge during the warmer months, a characteristic change expected as a result of global warming (Seidel et al 2008) and which current observations indicate is already occurring (Nguyen, 2013). This would result in a greater frequency of high pressure in favourable locations, often to the east of Tasmania, with more easterly airstreams being recorded, and fewer days of westerly weather. It would also result in drier warm season conditions in western Tasmania, as identified in other recent research work (Love et al., 2016a, 2016b). To conclude, the absence of projected changes to spring synoptic typing, and decreases in summer and autumn strong westerly streams are not expected to restrict future opportunities for prescribed burning.


No. of annual NW days/year
No. of annual N days/year
No. of annual NE days/year
No. of annual E days/year
No. of annual SE days/year
No. of annual S days/year
No. of annual SW days/year
No. of annual W days/year
No. of annual AC days/year
Days per year
Year
1980
2020
2060
2100

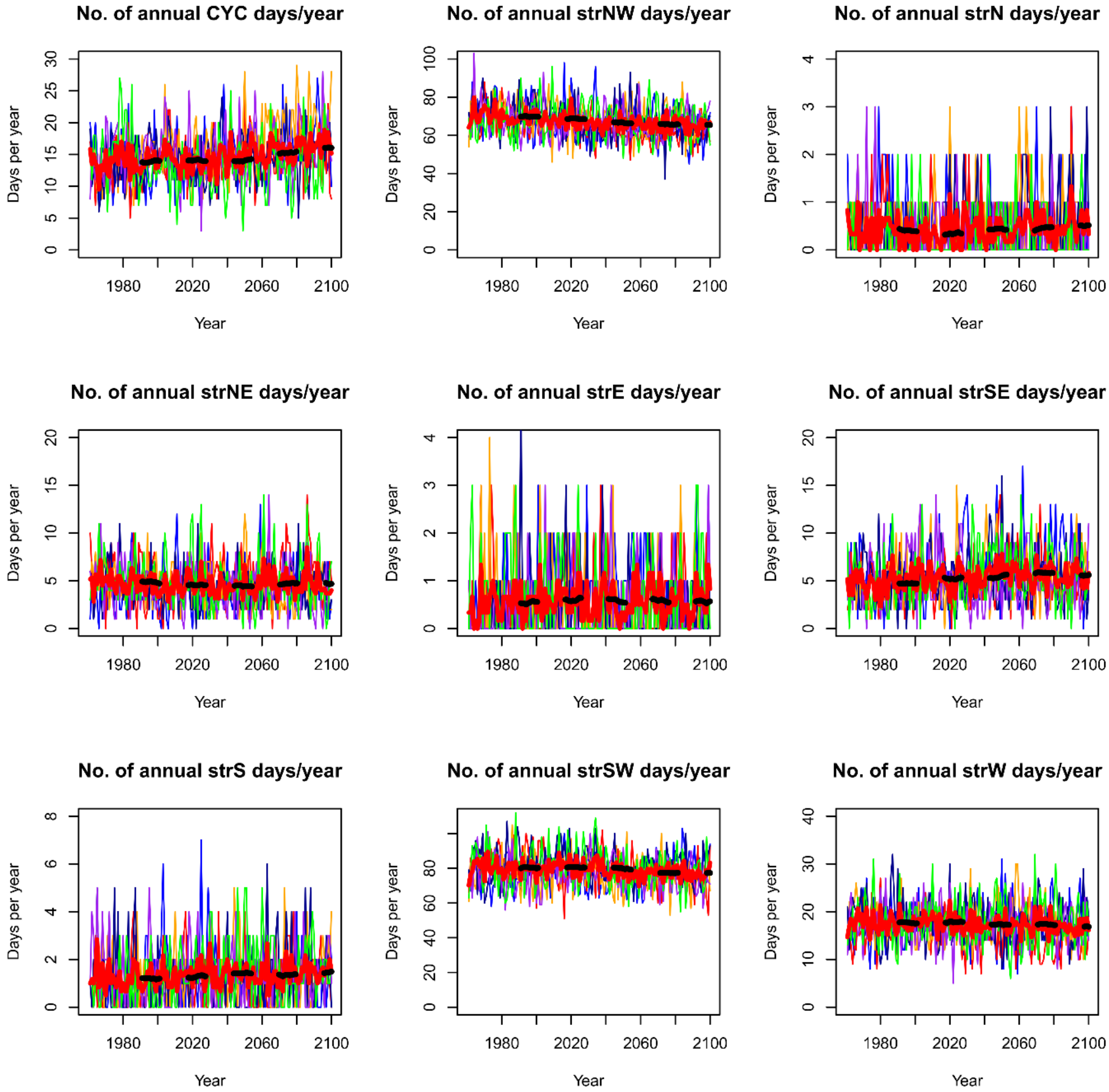
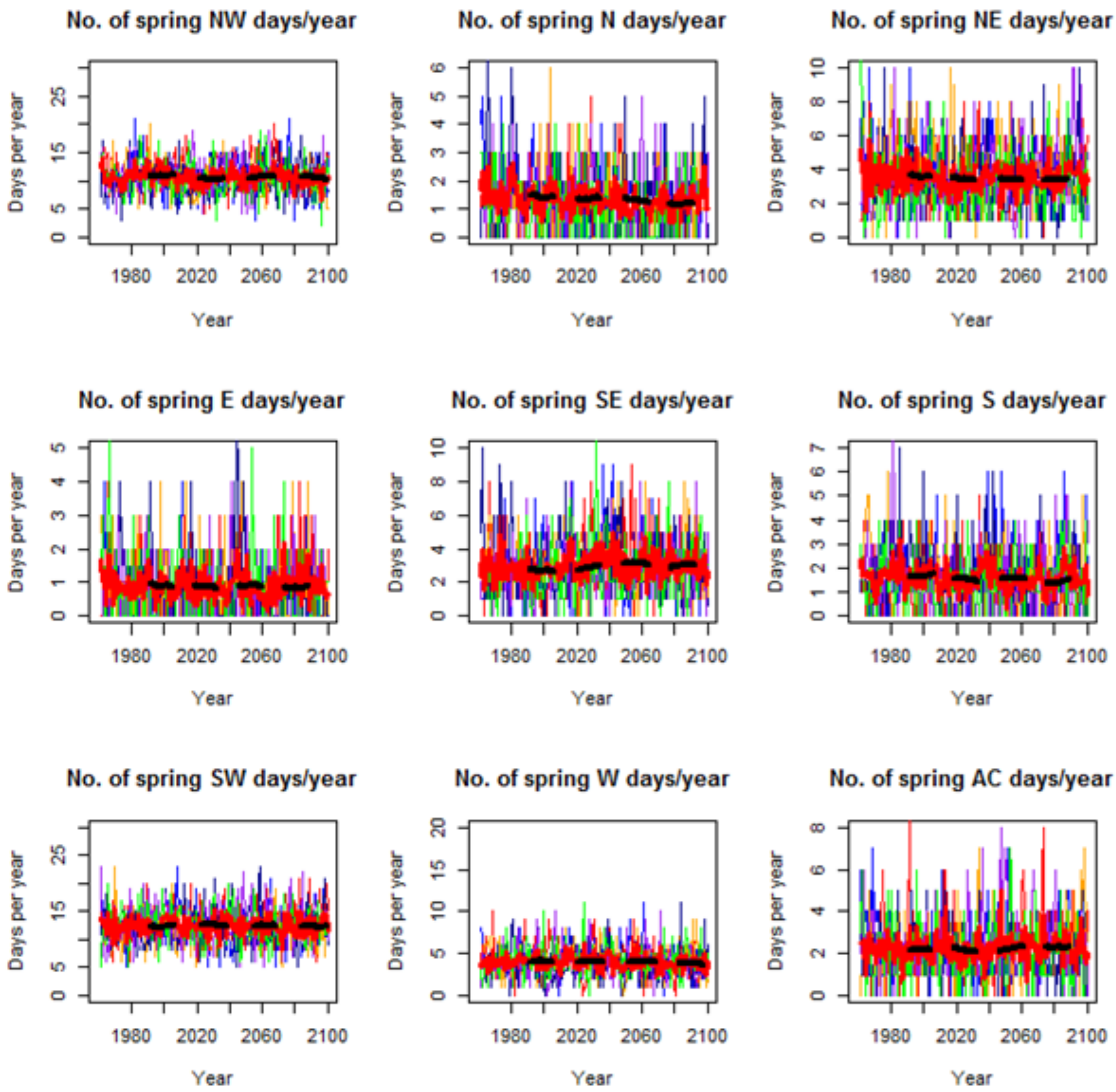


Figure 2.3: Changes in annual frequencies of synoptic patterns. Annual counts of each model are displayed as thin lines, the multimodel mean of the annual count is the bold red line, and the 30 year running mean of the multimodel mean is the black dashed line. (AC = Anticyclonic, CYC= Cyclonic, the "str" prefix indicates strong winds)


No. of spring NW days/year
No. of spring N days/year
No. of spring NE days/year
No. of spring E days/year
No. of spring SE days/year
No. of spring S days/year
No. of spring SW days/year
No. of spring W days/year
No. of spring AC days/year
Days per year
Year
1980
2020
2060
2100

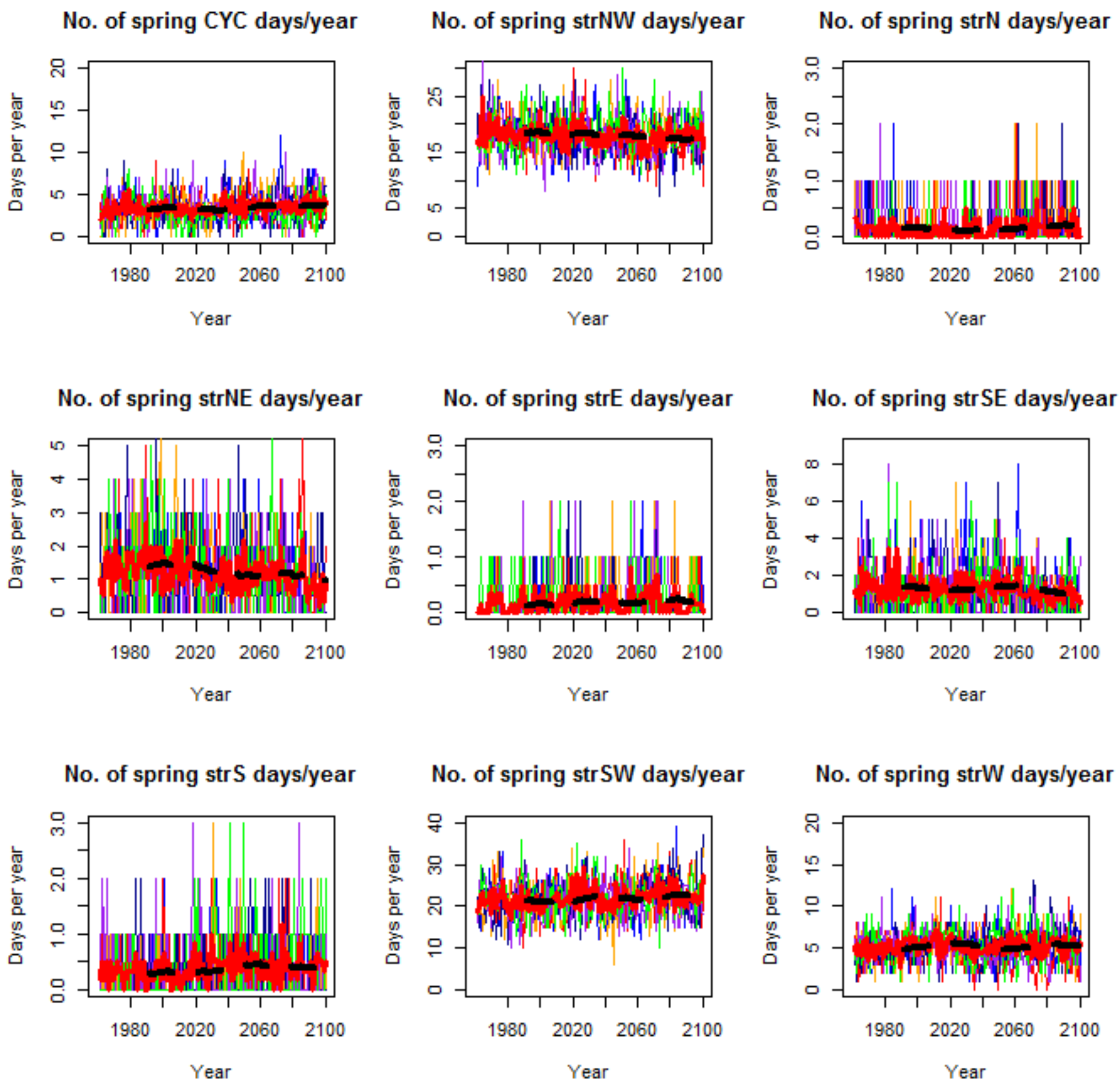
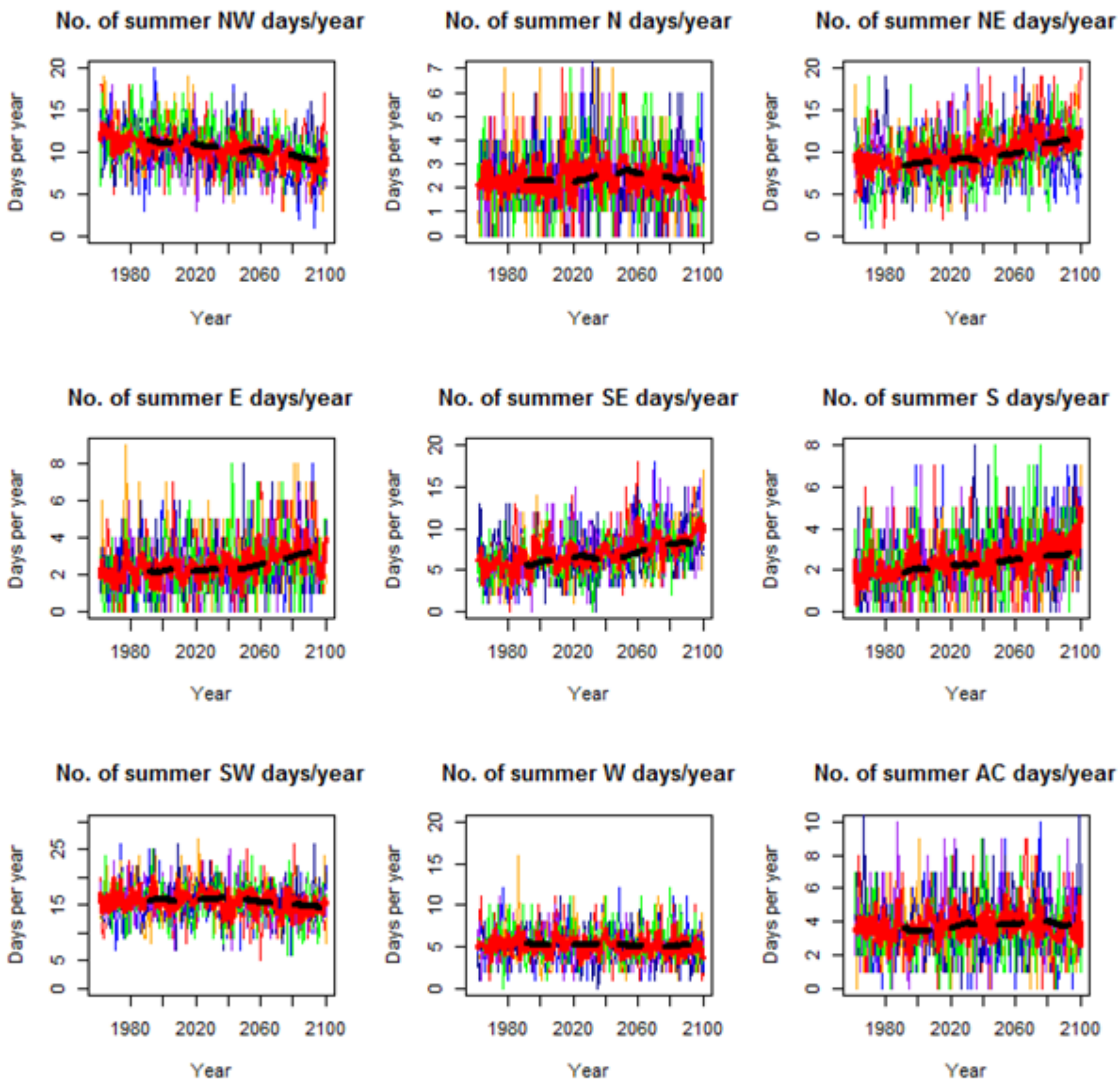


Figure 2.4: Changes in spring frequencies of synoptic patterns. Annual counts of each model are displayed as thin lines, the multimodel mean of the annual count is the bold red line, and the 30 year running mean of the multimodel mean is the black dashed line. (AC = Anticyclonic, CYC= Cyclonic, the “str” prefix indicates strong winds)


No. of summer NW days/year
No. of summer N days/year
No. of summer NE days/year
No. of summer E days/year
No. of summer SE days/year
No. of summer S days/year
No. of summer SW days/year
No. of summer W days/year
No. of summer AC days/year
Days per year
Year
1980
2020
2060
2100

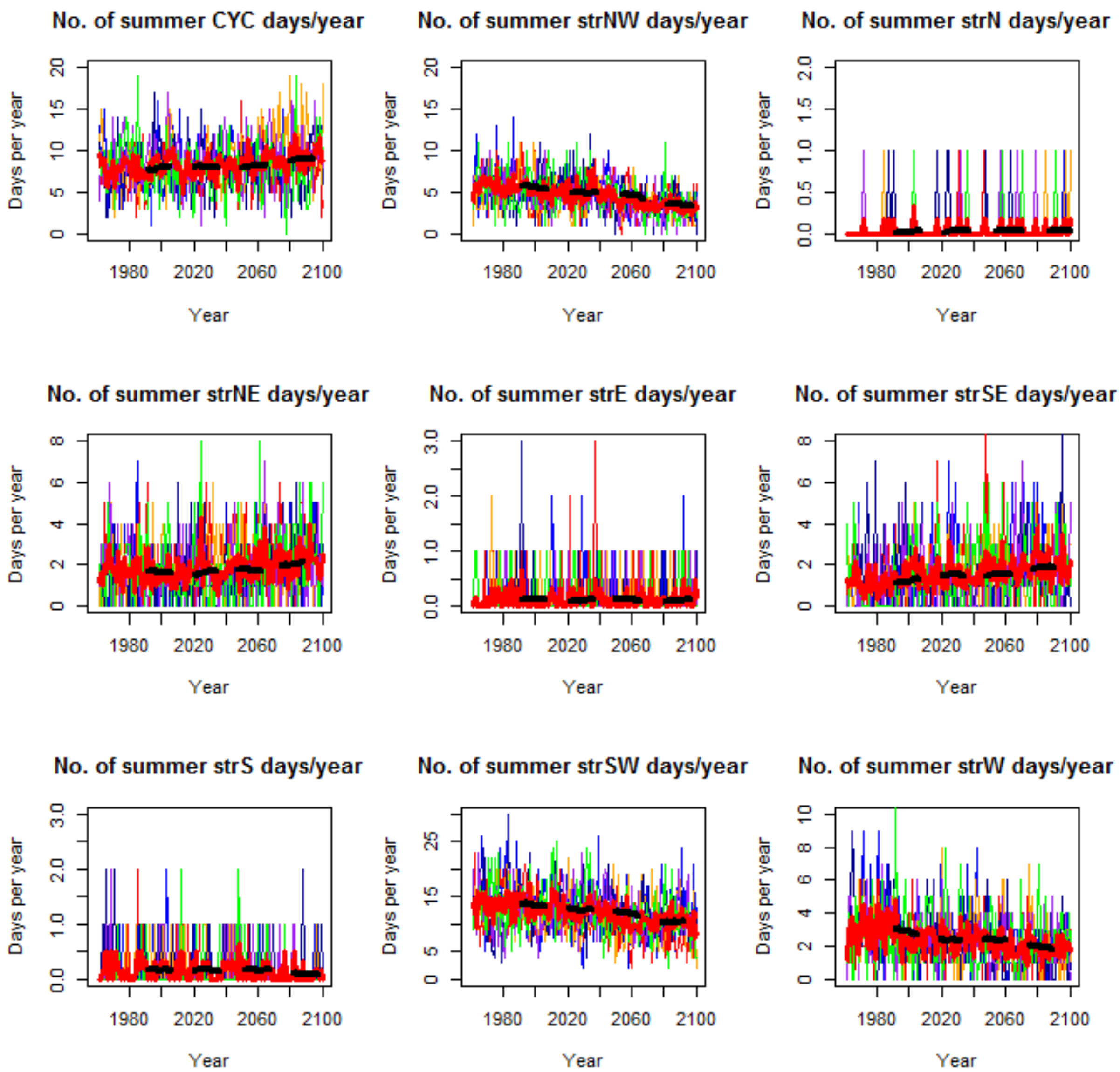
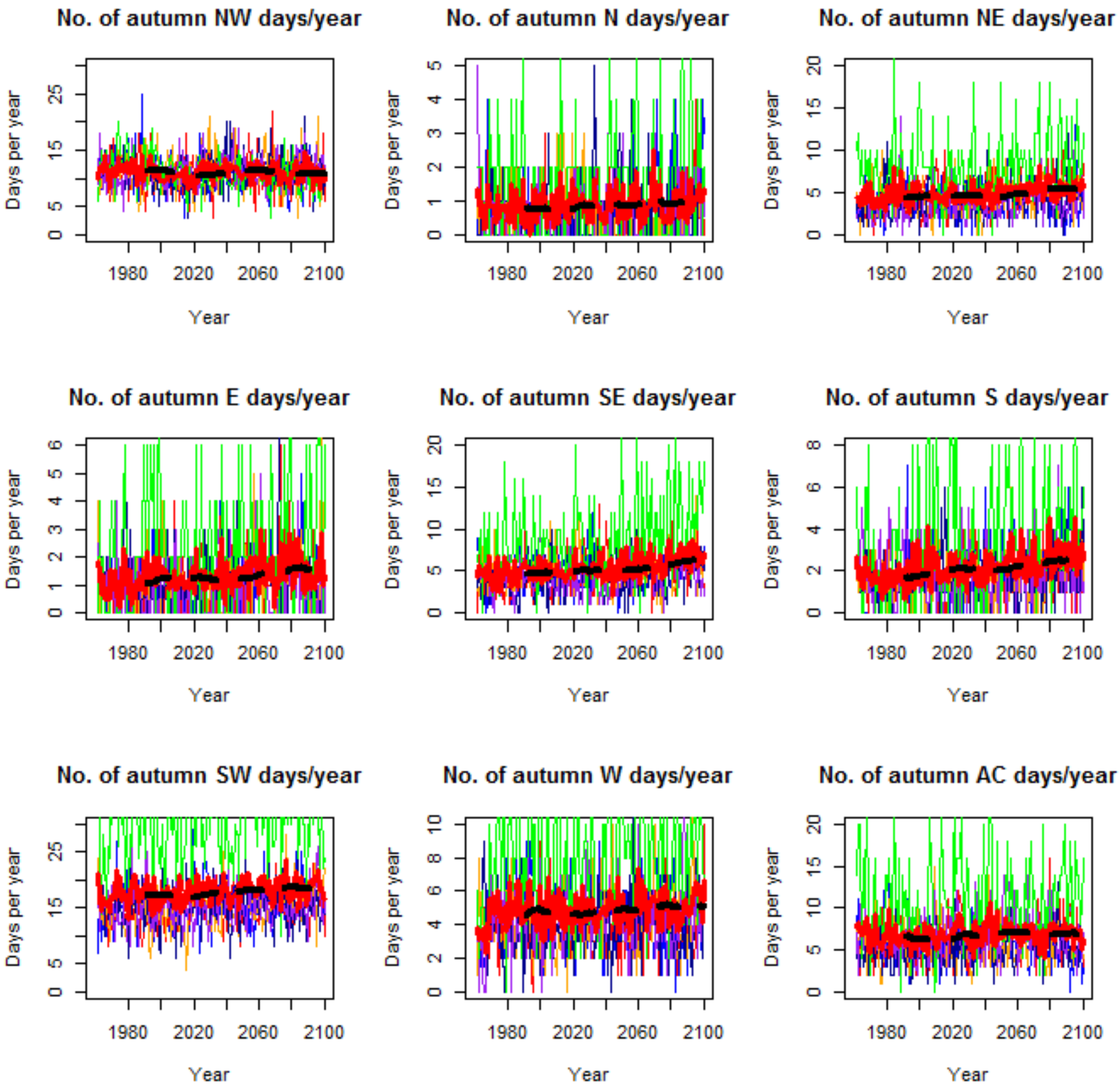


Figure 2.5: Changes in summer frequencies of synoptic patterns Annual counts of each model are displayed as thin lines, the multimodel mean of the annual count is the bold red line, and the 30 year running mean of the multimodel mean is the black dashed line. (AC = Anticyclonic, CYC= Cyclonic, the "str" prefix indicates strong winds).


No. of autumn NW days/year
No. of autumn N days/year
No. of autumn NE days/year
No. of autumn E days/year
No. of autumn SE days/year
No. of autumn S days/year
No. of autumn SW days/year
No. of autumn W days/year
No. of autumn AC days/year
Days per year
Year
1980 2020 2060 2100

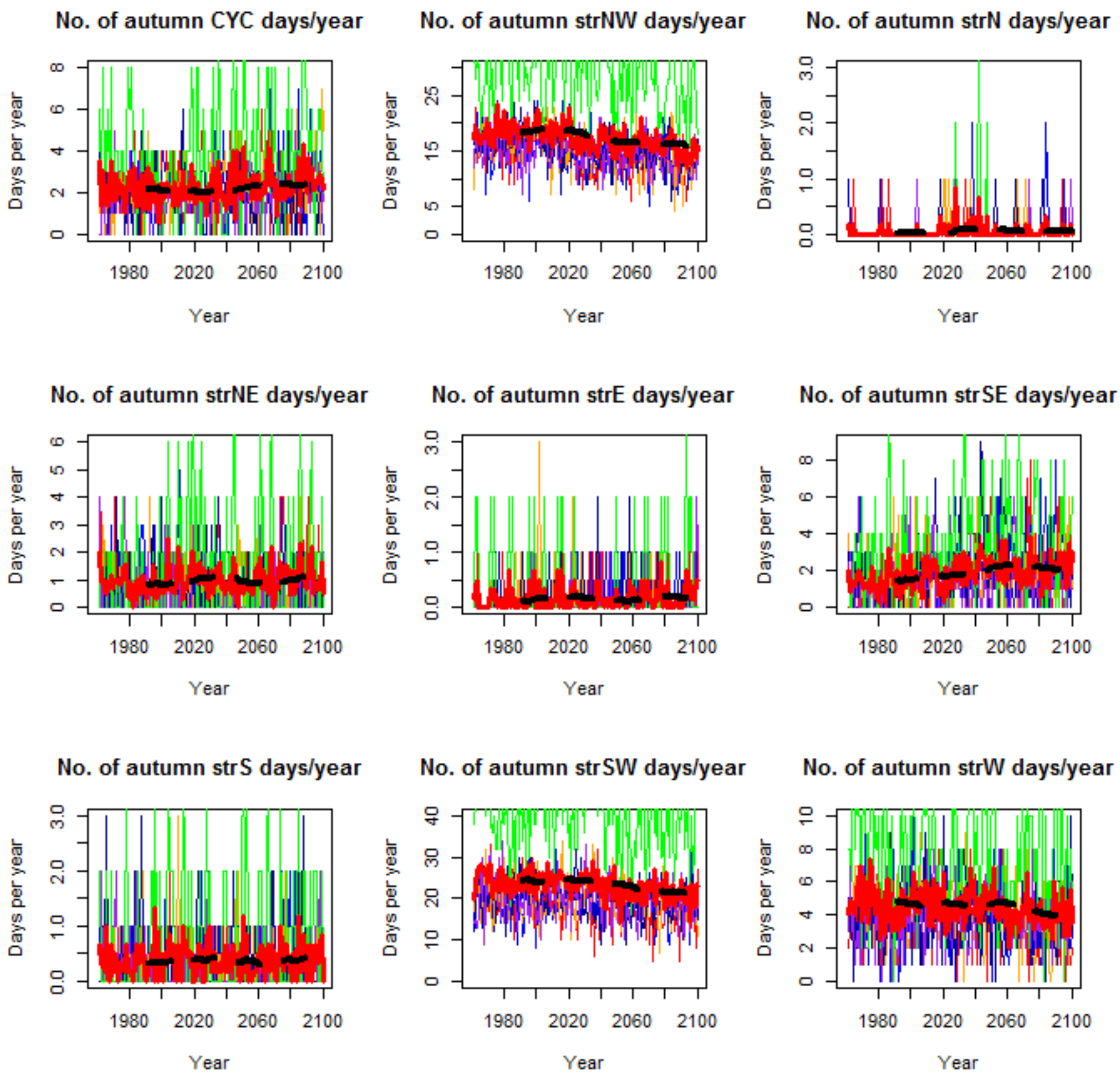
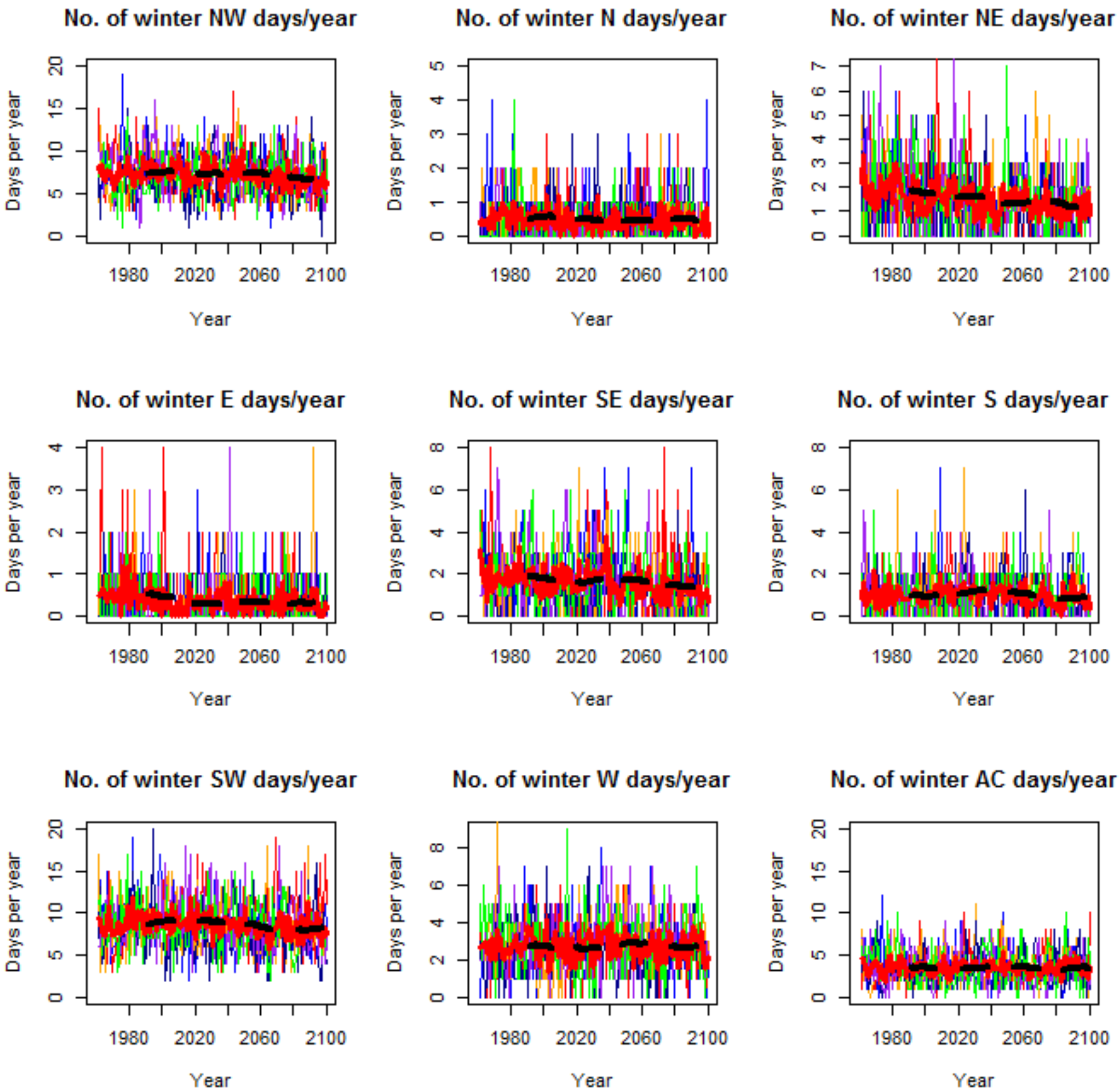


Figure 2.6: Changes in autumn frequencies of synoptic patterns. Annual counts of each model are displayed as thin lines, the multimodel mean of the annual count is the bold red line, and the 30 year running mean of the multimodel mean is the black dashed line. (AC = Anticyclonic, CYC= Cyclonic, the “str” prefix indicates strong winds).


No. of winter NW days/year
No. of winter N days/year
No. of winter NE days/year
No. of winter E days/year
No. of winter SE days/year
No. of winter S days/year
No. of winter SW days/year
No. of winter W days/year
No. of winter AC days/year
Days per year
Year
1980
2020
2060
2100

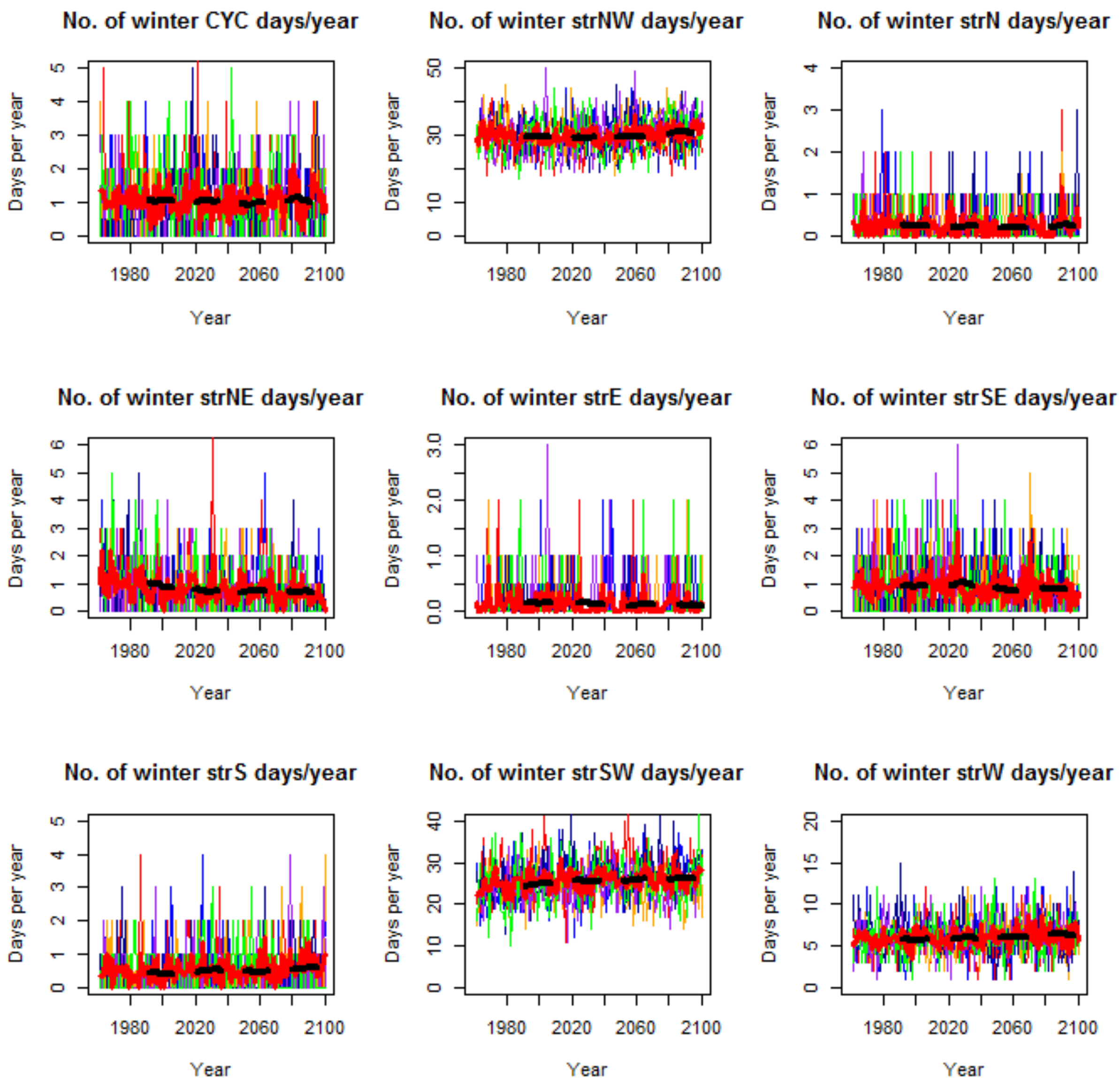


Figure 2.7: Changes in winter frequencies of synoptic patterns. Annual counts of each model are displayed as thin lines, the multimodel mean of the annual count is the bold red line, and the 30 year running mean of the multimodel mean is the black dashed line. (AC = Anticyclonic, CYC= Cyclonic, the "str" prefix indicates strong winds).

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Part 3 - Exploring the future of fuel loads in Tasmania. Shifts in vegetation in response to changing fire weather, productivity, and fire frequency.

3.1 Introduction

Vegetation mediates the interaction between fire and climate, since one of the key determinants of fire activity is the available fuel. The fuel's characteristics are influenced at the landscape scale by community structure and composition (e.g. grassland vs forest), and at more local scales by fuel age, structure and composition; rates of decomposition, which affect the litter depth, structure and composition; and vegetation growth rates. Attempts to project future fire danger must therefore account for changes in vegetation growth and fuel dynamics under future climatic conditions. The challenges associated with quantifying these processes have been identified as a significant gap that limits our ability to project future fire danger (Harris et al. 2016; Hennessy et al. 2005).

Estimating fuel characteristics under future conditions is complicated by the interactions that exist between the fire regime, vegetation, climate and human intervention (Harris et al. 2016). Feedbacks between these factors can lead to changes in the vegetation, which in turn influence the fire regime. However, while there are major impediments to projecting fuel loads under future climatic conditions, we are able to project several important factors determining fire activity into the future. In Tasmania, values for future climate conditions, including fire weather, Soil Dryness Index and productivity are available from the Climate Futures for Tasmania project. For other factors we know the general trends expected under climate change, allowing potential pathways of change to be identified, starting with the current flammability and sensitivity to fire of broad vegetation types.

The frequency of fire is an important aspect of the fire regime. Changes to the frequency of fire due to management decisions and climate change has the potential to affect the flammability of the vegetation, with long term effects on the vegetation structure and composition. Frequent fire in some vegetation types can lead to transformational change when a threshold is crossed, beyond which the vegetation type is radically altered, and this is not always a gradual process. For example, in forests dominated by obligate seeders, increased frequency of intense fire can cause a state change from woodland to grassland (Bowman et al. 2014). In Tasmania, changes to anthropogenic burning have caused rainforest to shift to moorland and vice-versa (di Folco and Kirkpatrick 2013; Fletcher and Thomas 2010a; Fletcher and Thomas 2010b). An increase in the frequency of prescribed burning may also increase flammability in some vegetation types (Fernandes and Botelho 2003; Lindenmayer et al. 2011). In subalpine and alpine forests of south-eastern Australia, for example, Zylstra (2013) demonstrated that frequent burning (up to a 14-year cycle) led to changes in forest structure that more than doubled the average size of fires, which spread faster and were more difficult to suppress.

Prescribed burning regimes are likely to change in the future, in response to shifts in community attitudes, resourcing, or a narrowing window available for burning. For this reason, in this report we explore future potential fire activity in Tasmania under different scenarios of fire frequency. We present an approach to identify the main drivers of change to potential fire activity under future climate change and explore potential pathways of change to broad vegetation types affecting flammability across the landscape. We use a “pathway modelling” approach to consider multiple transitional pathways that may occur under different fire frequencies. We do not include changes to the distribution of vegetation in response to changing climate suitability because we expect that such change will occur slowly over long timeframes for the main forest types in Tasmania. Since the dominant forest species that make up the bulk of the fuel load are long-lived and adapted to a broad range of climate conditions (as shown by their current broad geographical distributions), they are likely to persist, even if stressed, for much of the 100-year timeframe covered by the model.

While the model involves a considerable simplification of the real world of vegetation and fire at the landscape scale, the approach enables a range of plausible futures to be explored and provides a framework for considering the vegetation responses and feedbacks that may occur between fuel loads and fire weather in the future. It is not intended as a predictive model of vegetation flammability or spread under future conditions. Rather, it is a tool to explore the range of plausible futures arising from changing fire weather over time in combination with changes to the fire regime due to management decisions.

3.2 Methods

3.2.1. Modelling Potential fire activity

The vegetation pathway model is based on the four switch model (Bradstock 2010), which describes fire activity in terms of four factors that must be fulfilled simultaneously (switched "on") for fire to occur. There must be fuel available (biomass); it must be dry enough to burn (availability to burn); weather conditions must be conducive to fire spread (fire weather), and there must be an ignition source (ignition).

The "Potential fire activity", the level of fire activity possible if an ignition source were present, was calculated at each grid cell (10km) across Tasmania using the following equation:

Potential fire activity = Biomass + Availability to burn + Fire Weather

= (Productivity * Fuel load at time since fire) + (Flammability of Veg Type at that SDI* Slopefactor) + FDI

The layers used to calculate each term, and their relationship to each other, are presented in Figure 3.1. Each term is described in detail in Appendix 3.

Potential fire activity was calculated at seven time periods (1961–1980, 1981-2000, 2001-2020, 2021-2040, 2041–2060, 2061-2080, 2081–2100) under a range of fire frequency scenarios. Mean values for each term were calculated for current and future time periods using a combination of spatial layers calculated from the Climate Futures for Tasmania climate data (Productivity, SDI, Forest Fire Danger and Moorland Forest Danger Indices), attributes from TasVeg 3.0 (DPIPWE 2013), and information on fuel characteristics from the scientific literature.

3.2.2. Representing the response to fire of Tasmanian vegetation communities

TasVeg 3.0 (DPIPWE 2013) was used to provide information about the composition, structure, flammability and fire sensitivity of broad vegetation groups. This provided the baseline for the potential response of the vegetation to changing fire weather, productivity (biomass), and fire frequency. TasVeg 3.0 provides a map of the Tasmanian vegetation at a resolution of 1:25 000, comprised of 158 mapping units, most of which represent distinct vegetation communities. Associated with each mapping unit is detailed information about the composition, structure and floristics of the unit (Harris and Kitchener 2005), from which flammability and fire sensitivity categories have been derived based on the attributes of the common plant species (Pyrke and Marsden-Smedley 2005). We focus on the dominant plants because they are often the “fuel species” (Gill et al. 1999) that provide most of the biomass and determine the structure of the vegetation community. Changes to the distribution, abundance or dominance of fuel species under altered fire regimes have the potential to set up positive or negative feedbacks.

The response of a community to fire is related to the flammability and sensitivity of the present vegetation type to fire. The fire-attributes categories (24 categories) are groups of TASVEG communities that have similar fire sensitivity and flammability characteristics. There are five fire sensitivity categories (low, moderate, high, very high and extreme) which reflect the potential ecological impact of a single fire on a stand of vegetation. Sensitivity to fire will determine the response of the vegetation to fire, or alternatively, its resilience to frequent burning. Sensitivity is influenced by the reproductive strategy of the dominant species (e.g. obligate seeders vs resprouters, time to maturity) (Noble and Slatyer 1980), which has been widely used to represent response to changing fire intervals (e.g. Hammill et al. 2016). The four flammability categories (low, moderate, high, and very high) are based on knowledge of the dynamics of fuel dryness for each vegetation type, which affects how many days per year the vegetation type will burn. The distribution of vegetation across Tasmania belonging to the flammability categories in TasVeg3.0 is shown in Figure 3.2. Flammability is comparable to the classification of vegetation communities into ‘fuel groups’ in fire management plans in New South Wales and the national Bushfire Fuel Classification. The categories are defined in Table 3.1.

We use a broad functional type approach to understand the effect of altered fire regimes across the landscape, because it is independent of taxonomic identity, and therefore focusses on process (Cary et al. 2012). Different species assemblages may have very similar fuel properties, because it is strongly influenced by vegetation structure and spatial distribution (Bradstock et al. 2012).

Table 3.1: Fire sensitivity and Flammability categories from Pyrke and Marsden-Smedley (2005).

Fire Sensitivity Categories:	
Extreme	**Any fire will cause irreversible or very-long-term (>500 years) damage**
Very high	**A single fire will cause significant change to community structure for 50–100 years and will increase the probability of subsequent fires**
High	**At least 30 years between fires is required to maintain the defining species. Fire intervals greater than 80 years are required to reach mature stand structure**
Moderate	**At least 15 years between fires is required to maintain the defining species**
Low	**A single fire will generally not affect the vegetation, but repeated short intervals (i.e., <10 years) may cause long-term changes**
Flammability Categories	
Very high	**Will burn readily throughout the year even under mild weather conditions, except after recent rain (i.e., less than 2–7 days ago)**
High	**Will burn readily when fuels are dry enough (from late spring to early autumn) but will be too moist to burn for lengthy periods, particularly in winter**
Moderate	**Will only burn after extended periods without rain (i.e., 2 weeks or more), and in moderate or stronger wind conditions**
Low	**Will burn only after extended drought (i.e., 4 weeks or more without rain) and/or under severe fire weather conditions (i.e., Forest Fire Danger Index > 40)**

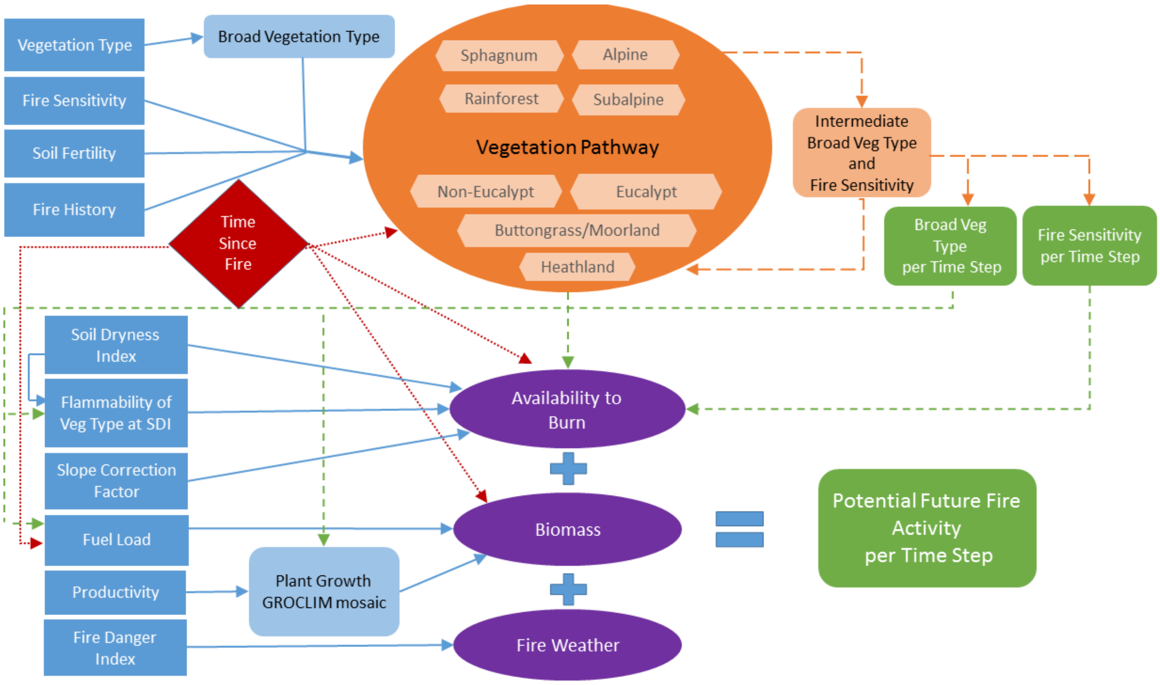

Figure 3.1: The components of the vegetation transition model. Blue boxes are inputs. Light-blue boxes are derived products. Orange components represent the different vegetation pathways followed over time. Purple boxes represent the "switches" calculated. Green boxes are outputs reflecting changes to vegetation over time. 'Broad Vegetation Type per timestep' is used to define the vegetation conditions and estimate the Potential Fire Activity at each timestep.

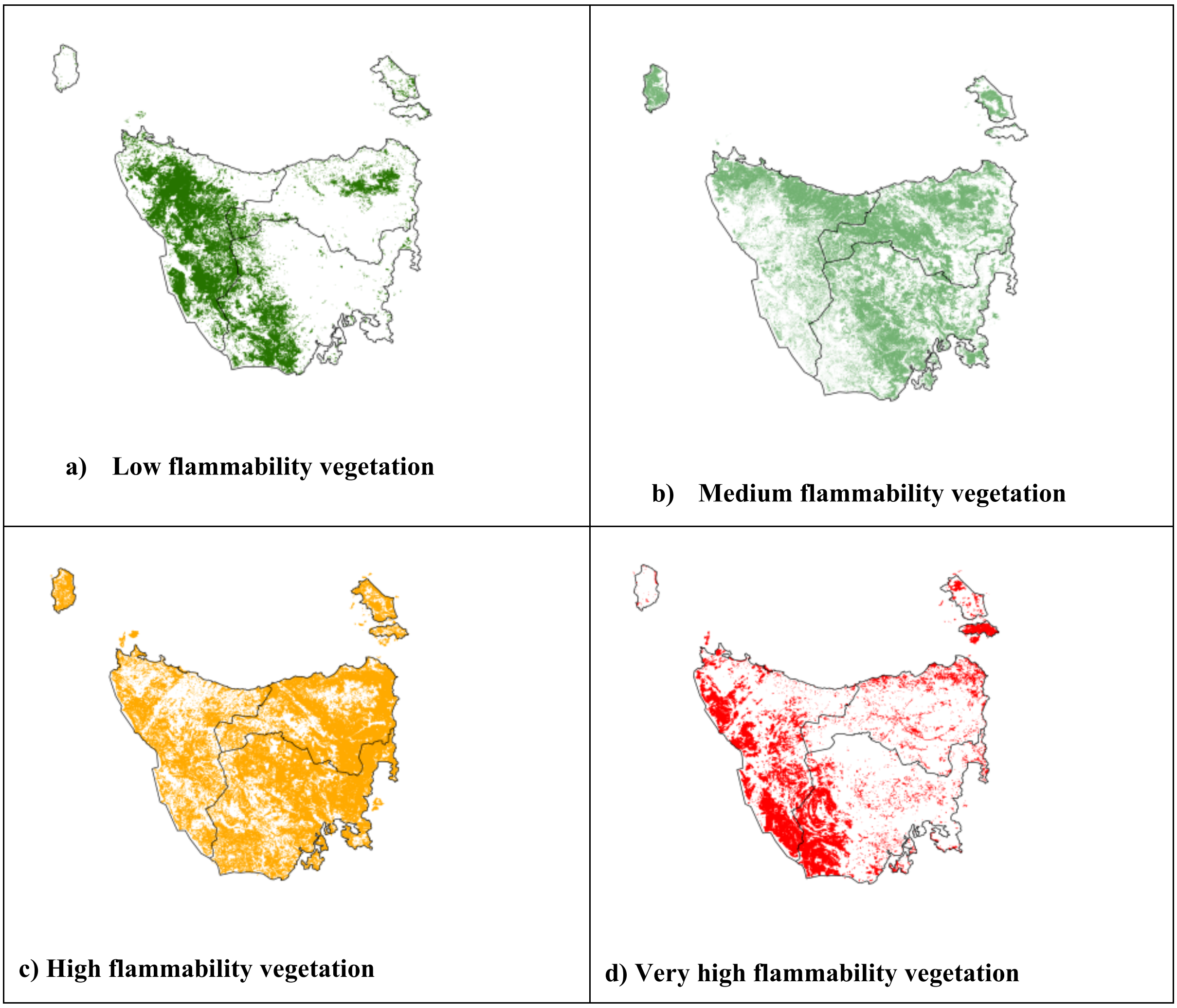

Figure 3.2: The distribution of vegetation across Tasmania belonging to the flammability categories in TasVeg3.0

3.2.3. Vegetation pathways through time

The model starts with broad vegetation type to determine the general transition pathway, but the rate at which change occurs is based on the attributes of the underlying mapping units. Transitional gradients, from wet forest types through to dry forests, woodlands and grasslands, are followed, dependant on the fire frequency and the changing fire weather over time.

Eucalyptus forests, non-eucalyptus forests (e.g. *Melaleuca*, *Leptospermum*, *Acacia*) and rainforests (e.g. *Athrotaxis*, *Nothofagus*) follow different pathways, represented by a gradient of moisture and fire frequency (see Table 3.2). Subalpine and alpine types are treated separately to reflect their higher sensitivities to fire. The pathways can be reversed under fire suppression scenarios except where site factors determine the present vegetation type. For example, grassland can move towards forest if fire is suppressed, and non-eucalypt wet forest may become drier in the future and with increased fire frequency. However, dry non-eucalypt forests can't become wet forests because the current composition reflects the moisture of the site (e.g. *Allocasuarina* occurs on dry sites, *Acacia* on wet sites).

Different understorey types within the broad vegetation types reflect the fertility of the site, moisture and fire history. We assigned broad understorey types to enable this to be incorporated into the transition pathway and influence the rate of change. We started all communities with the understorey it would have if it had been unburnt for long periods. We did not attempt to recreate the state of the vegetation in its current state, although this could be incorporated with further model development.

Fire sensitivity was changed at each time step to reflect any changes to vegetation type, based on the assumption that the vegetation community will shift in the direction of lower fire sensitivity (ie. more fire adapted) if the fire interval is shorter than the interval that the original community requires to maintain the defining species. For example, a vegetation type in the Extreme category moves one step to the Very High category if the fire interval is less than 500 years, because any fire will cause either irreversible or very long-term (> 500 years) damage (Pyrke and Marsden-Smedley 2005). A fire-adapted community with Moderate fire sensitivity will move one step to the Low category if the fire interval is less than 15 years and remain at Moderate if the fire interval is greater than 15 years, because vegetation communities in this category require at least 15 years between fires to maintain the defining species. Conversely, a Grassland with Low fire sensitivity can move in the other direction if fire is excluded for more than 100 years, as the community shifts towards a more mesic vegetation type. Flammability was also updated at each time step to reflect any changes to vegetation type.

Table 3.2: The transition pathways for the broad vegetation types

Forest type	
Eucalyptus	**Wet sclerophyll forest with Rainforest understorey (Mixed forest) – Wet sclerophyll forest broadleaf tree understorey - Wet sclerophyll forest with shrubby/heathy understorey – Dry sclerophyll forest shrubby/heathy understorey – Dry sclerophyll forest grassy understorey – Woodland Shrubby/Heathy understorey** – Woodland Grassy understorey – Grassland**
Non-eucalyptus	**Non-eucalypt Wet Forest shrubby/broadleaf/heathy understorey - Wet scrub shrubby understorey – Wet scrub heathy understorey – Dry scrub – Heathland – Grassland – Bare Ground**
Rainforests	**Rainforest with conifers and/or deciduous beech – Rainforest without conifers or deciduous beech – Wet scrub shrubby understorey – Wet scrub heathy understorey - Heathland – Sedgeland/buttongrass moorland (low fertility, poor drainage) /Grassland (better soils) – Bare Ground**
Buttongrass Moorland	**Buttongrass moorland woodland shrubby or heathy understorey -– Buttongrass Moorland – Bare Ground**
Alpine	**Alpine Heathland with conifers - Alpine Heathland without conifers – Alpine Rushland/Sedgeland (including bare ground)**
Subalpine	**Subalpine Rainforest – Subalpine Woodland - Subalpine Scrub - Subalpine heathland – Subalpine Sedgeland/Subalpine Grassland – Bare Ground**
Sphagnum	**Sphagnum – Rushland/Sedgeland – Bare Ground**

3.2.4. Fire Frequency

We explored the effect of different fire frequencies (or the fire interval in the equation above) on the potential fire activity and flammability of vegetation across Tasmania. The climate layers (productivity, SDI and fire weather) were updated to reflect the changing climate over time, and the vegetation type was shifted along the appropriate pathway when the fire frequency was above the threshold for each type. Values for the time between fires, or fire interval, required for recovery were based on available literature (e.g. Table 3.3).

Table 3.3: Fire sensitivity categories used in the vegetation model (from Pyrke and Marsden-Smedley 2005).

	Frequency of fire above which community does not survive (# fires per 100 years)	Return Interval (time between fires), below which community does not survive (stand replacement)	Return Interval (time between fires), below which community will change gradually
Extreme (E)	**1**	**300**	**500**
Very High (VH)	**1**	**50**	**100**
High (H)	**3**	**30**	**80**
Moderate (M)	**6**	**-**	**15**
Low (L)	**-**	**2-5**	**10**

3.3 Results

3.3.1 Impact of fire frequency on Vegetation Type

The Tasmanian operational guidelines for asset protection zones recommend fire frequencies of between 4 to 10 years in dry forests and scrub (See Table 1.14), and the exclusion of prescribed burning from the wet forests, alpine areas and other fire sensitive vegetation communities (Table 3.4). The results presented here therefore do not represent the current management approach to prescribed burning. Instead, we present a range of scenarios of fire frequency.

Frequent fire has the potential to lead to shifts in vegetation type, away from mesic, fire sensitive types, towards more open, fire adapted vegetation. The rate of change differs across the vegetation types, with some fire sensitive communities adversely impacted by even a single fire and requiring very long recovery times (500-1000 years). For example, rainforest communities with conifers may never recover after a fire, as *Athrotaxis* is an extremely slow growing and very long-lived tree that is killed by fire. In such communities there is a positive feedback where fires promote vegetation that is more flammable, increasing the risk of fire (Hill and Read 1984). In contrast, fire-adapted vegetation, such as dry eucalypt forests, recover relatively quickly after fire, and are only impacted by very frequent fires.

This can be illustrated in several ways. A map of Tasmania can be used to show the distribution of the different vegetation types, and how this changes at different fire intervals. At a statewide level, very frequent fire, with only 4 years between fires, results in a shift towards open vegetation types across the state (Figure 3.3). Regions of Tasmania with fire sensitive vegetation are highlighted, as the vegetation shifts quickly at high fire frequency. For example, the wet sclerophyll forests with rainforest or broadleaved understoreys in southern Tasmania (shown in orange) quickly move towards more open forest types. In contrast, at very long fire intervals (or low fire frequency), which would occur if fire were actively suppressed, some vegetation types could potentially transition towards different vegetation types (Figure 3.4). For instance, if fire were suppressed in native grasslands, there would be a shift towards woodland vegetation as trees establish in the absence of frequent fire. Buttongrass moorland transitions to a woody vegetation type (mauve to pink) if fire is suppressed and the fire interval is longer than 30 years (although this could take 75 years in low productivity sites). The regions of Tasmania with the greatest potential for vegetation transitions to occur is in the Central Plateau and Western districts, where fire sensitive vegetation types, such as alpine and subalpine vegetation and rainforests predominate.

Such changes have the potential to affect the state-wide distribution of structural types, which can be demonstrated by comparing the area of Tasmania with each broad type over time under different frequencies of fire (Figure 5). The bare ground category is used when the vegetation has been pushed beyond the limits of adaptability, and no vegetation is able to establish. If fires were to occur every two years for a period of 15 years, only grasslands and dry forests would remain, and many areas, such as alpine areas and sphagnum, would become bare ground. As the fire interval increases (e.g. to seven years), there is less of an impact on the fire-adapted vegetation types such as grasslands and woodlands, but there is still an increase in their area as the more mesic vegetation types transitions towards grassland and woodland. The area of forest appears stable at these fire frequencies, but there is a shift towards dry forest, away from wet eucalypt and non-eucalypt forests. The current area of woodlands can be sustained into the future at fire intervals above 16 years. At longer intervals, the area increases, as grasslands transition into woodlands when fire is suppressed. The dry eucalpyt forests and woodland types in which prescribed burning is currently carried out are sustained at a ten-year fire interval (Figure 3.6). The transitions are seen as a series of steps in the output, reflecting the threshold values used in the model. These values can be updated if improved empirical data were to become available for any vegetation type.

Table 3.4: Vegetation types not suitable for planned burning (from Pyrke and Marsden-Smedley 2005).

Vegetation types not suitable for planned burning
Alpine and subalpine heathland, with or without conifers and/or deciduous beech
Alpine native grassland
Rainforest, with or without conifers and/or deciduous beech
Damp eucalypt forest
Mixed forest
Wet forest
Sphagnum
Swamp and wetland

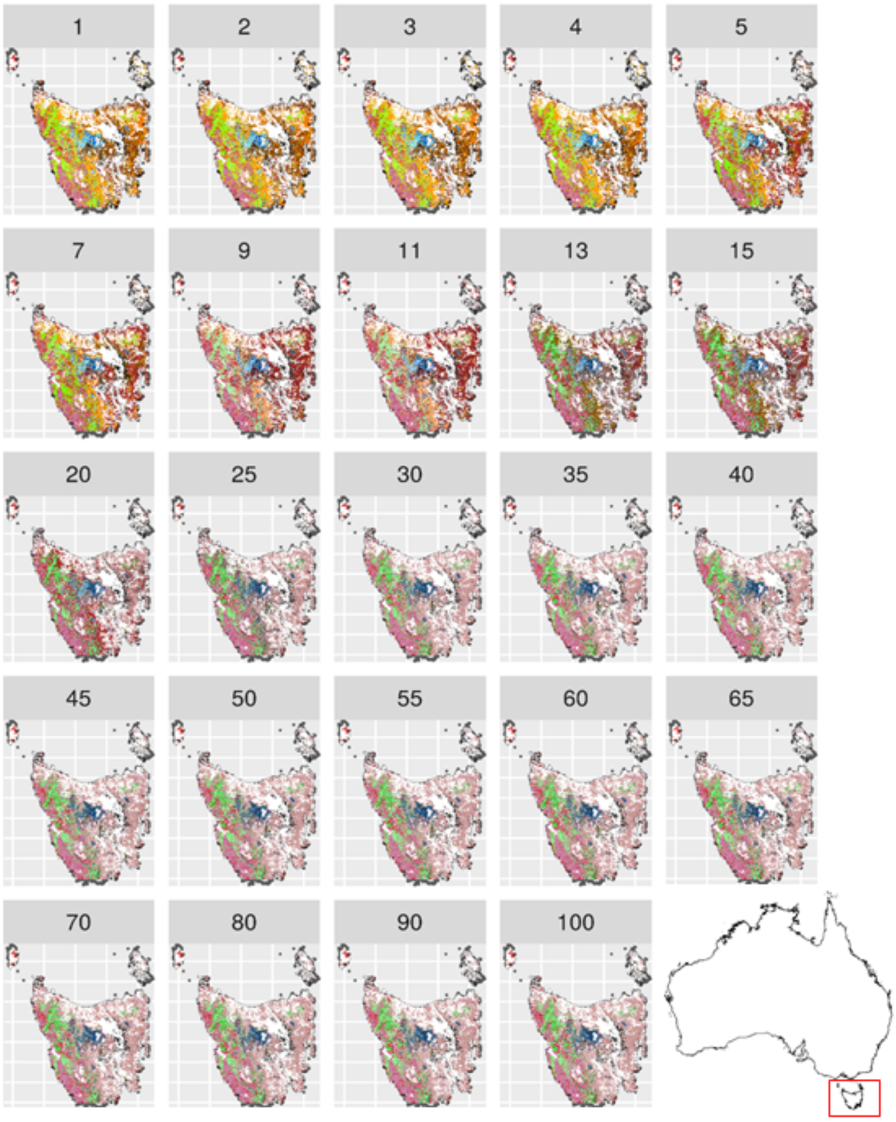

Figure 3.3: Impact of frequent fire (every 4 years) on vegetation type across Tasmania, incorporating annual layers from the Climate Futures for Tasmania projections. The numbers above each map refers to the number of years from 2000. Colours represent different vegetation types, as follows: Light blues, Subalpine vegetation; Dark blue, Alpine vegetation; Purple, Buttongrass; Oranges, Wet sclerophyll; Dark Orange to Brown, Dry sclerophyll; Greys, Woodland; Reds, Non-eucalypt wet forests; Dark Purple, Non-eucalypt dry forests, Light to Dark Greens, Rainforest.

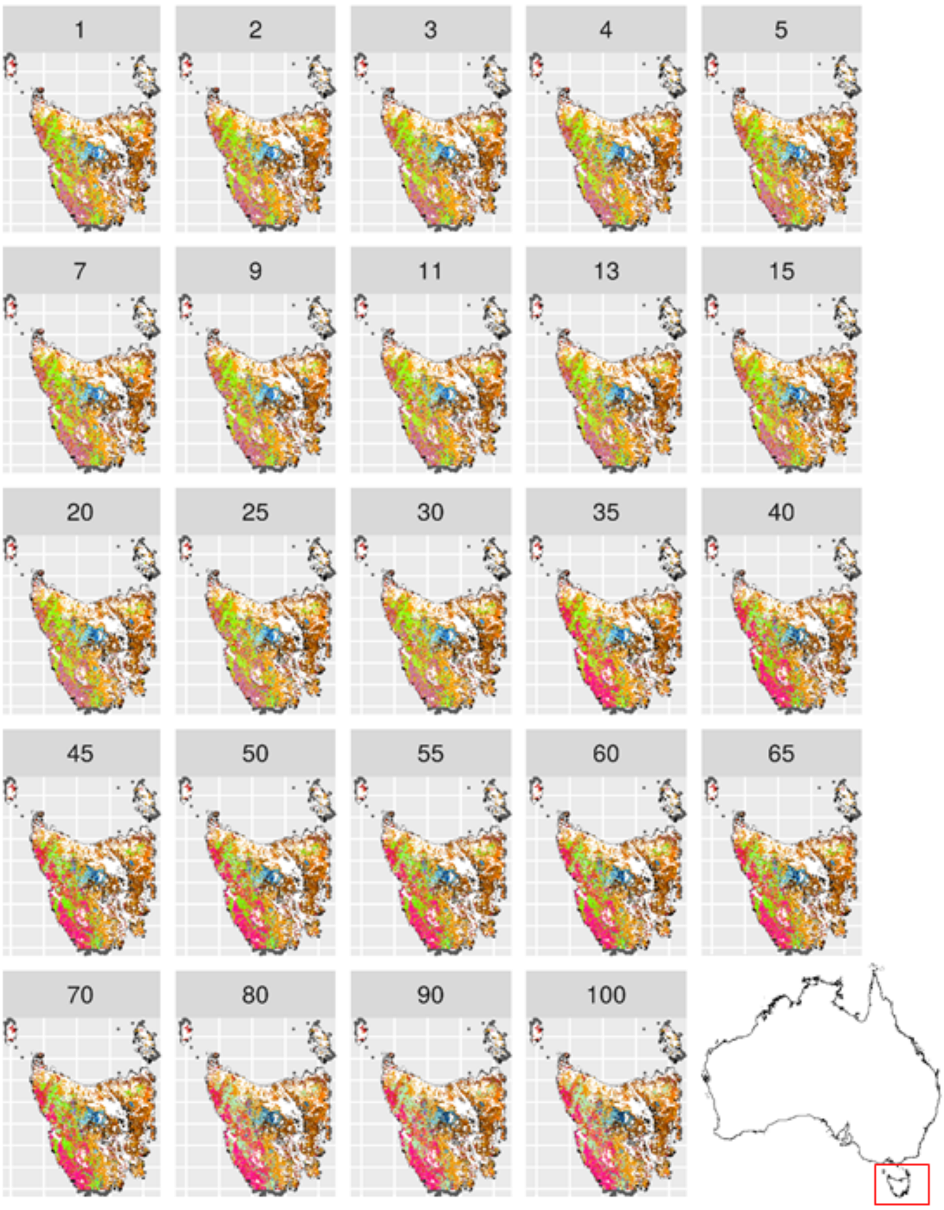

Figure 3.4: Impact of infrequent fire (every 33 years) on vegetation type across Tasmania, incorporating annual layers from the Climate Futures for Tasmania projections. The numbers above each map refers to the number of years from 2000. Colours represent different vegetation types, as follows: Light blues, Subalpine vegetation; Dark blue, Alpine vegetation; Purple, Buttongrass; Oranges, Wet sclerophyll; Dark Orange to Brown, Dry sclerophyll; Greys,

Woodland; Reds, Non-eucalypt wet forests; Dark Purple, Non-eucalypt dry forests, Light to Dark Greens, Rainforest.

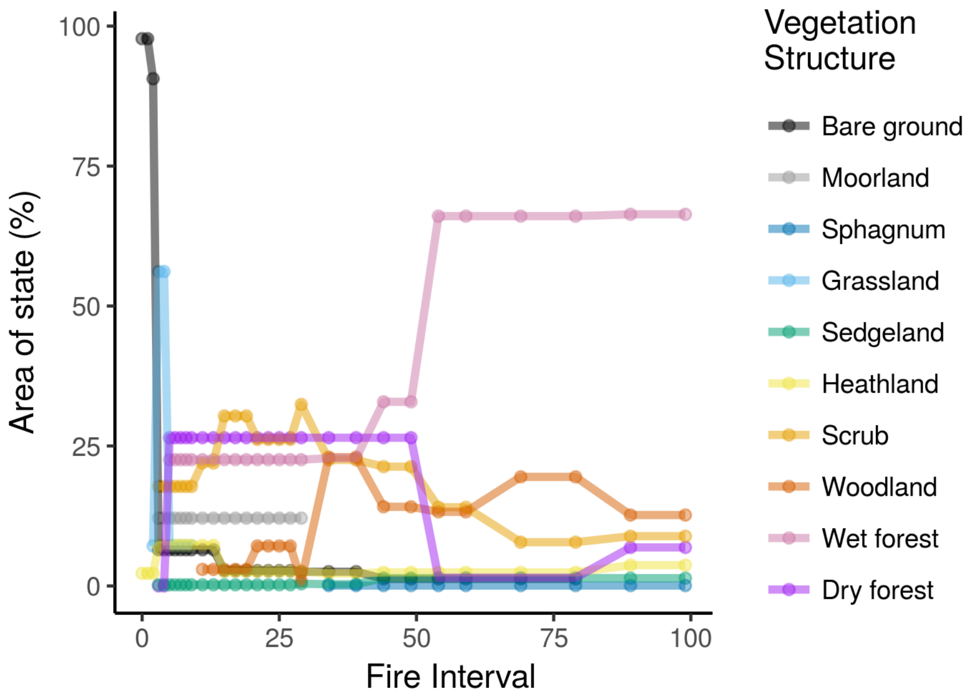

Figure 3.5: The change in the area of Tasmania covered by broad vegetation structural types after 100 years of burns at a range of fire intervals. The area at fire interval 0 corresponds to the distribution of vegetation types in the year 2000.

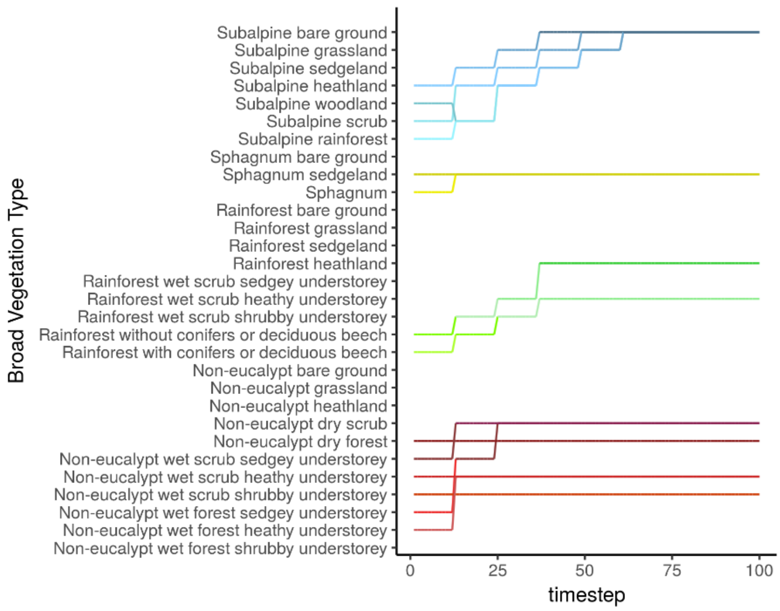

Figure 3.6: The impact of a ten-year fire interval on vegetation types across Tasmania over a period of 100 years, beginning in 2000. Transitions were constrained along vegetation pathways, indicated by different colours, with each type having different tolerances to fire frequency.

3.3.2 Impact of fire interval on future Potential Fire Activity

Fire frequency has a substantial impact on the future Potential Fire Activity (PFA) relative to the impact of the changing climate over the coming decades. Transitions towards drier vegetation types have important consequences for the PFA because of the link with flammability in drier, fire adapted vegetation types. With very high fire frequency (fire interval of 1-2 years), the PFA is very low because all vegetation is pushed towards the bare ground state in the model over time (Figure 3.7). Beyond 3 yearly intervals, the more frequent the fire, the lower distribution and the peak of the state-wide PFA. The highest PFA values are all at fire intervals greater than 30 years, reflecting the contribution of fuel accumulation and carrying capacity to fire activity.

Similar results can be generated for any region of Tasmania and will reflect the different vegetation types within the region of interest (Figure 3.8).

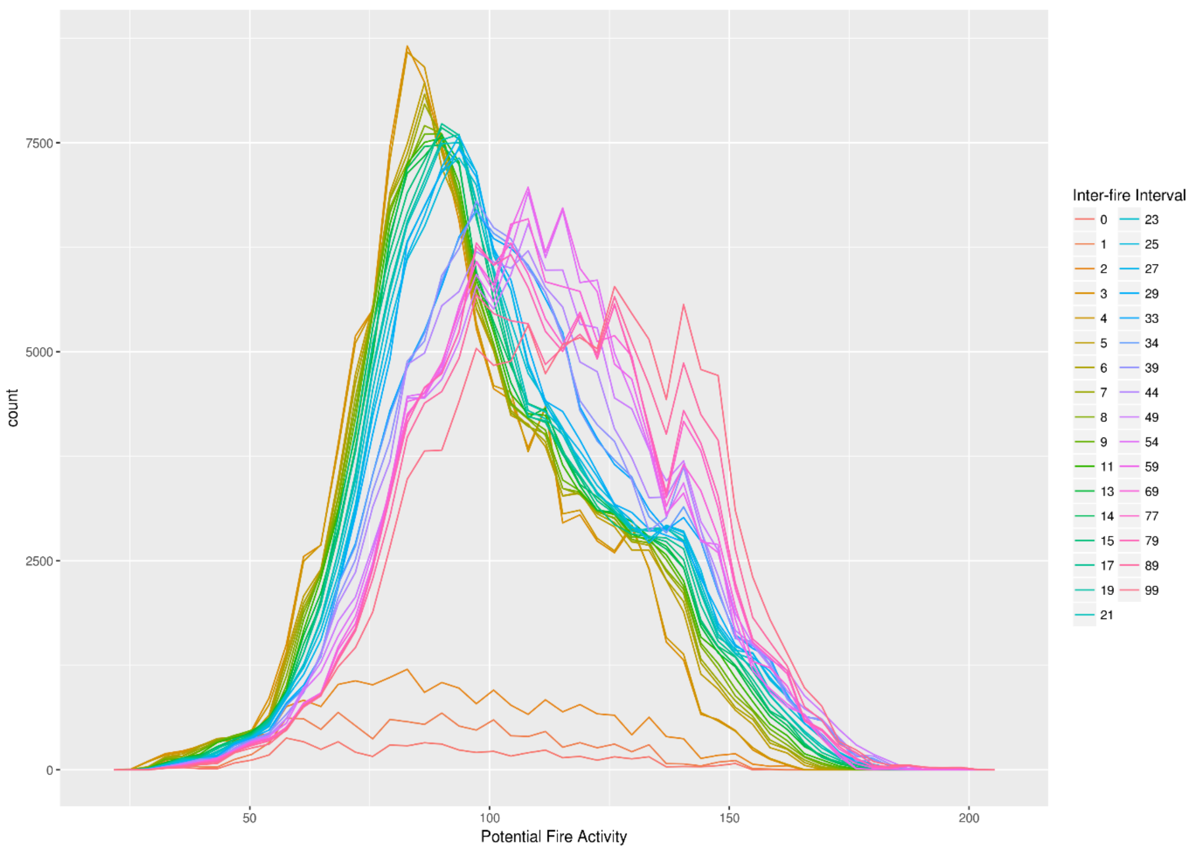

Figure 3.7: Impact of fire interval on future Potential Fire Activity (PFA) across Tasmania.

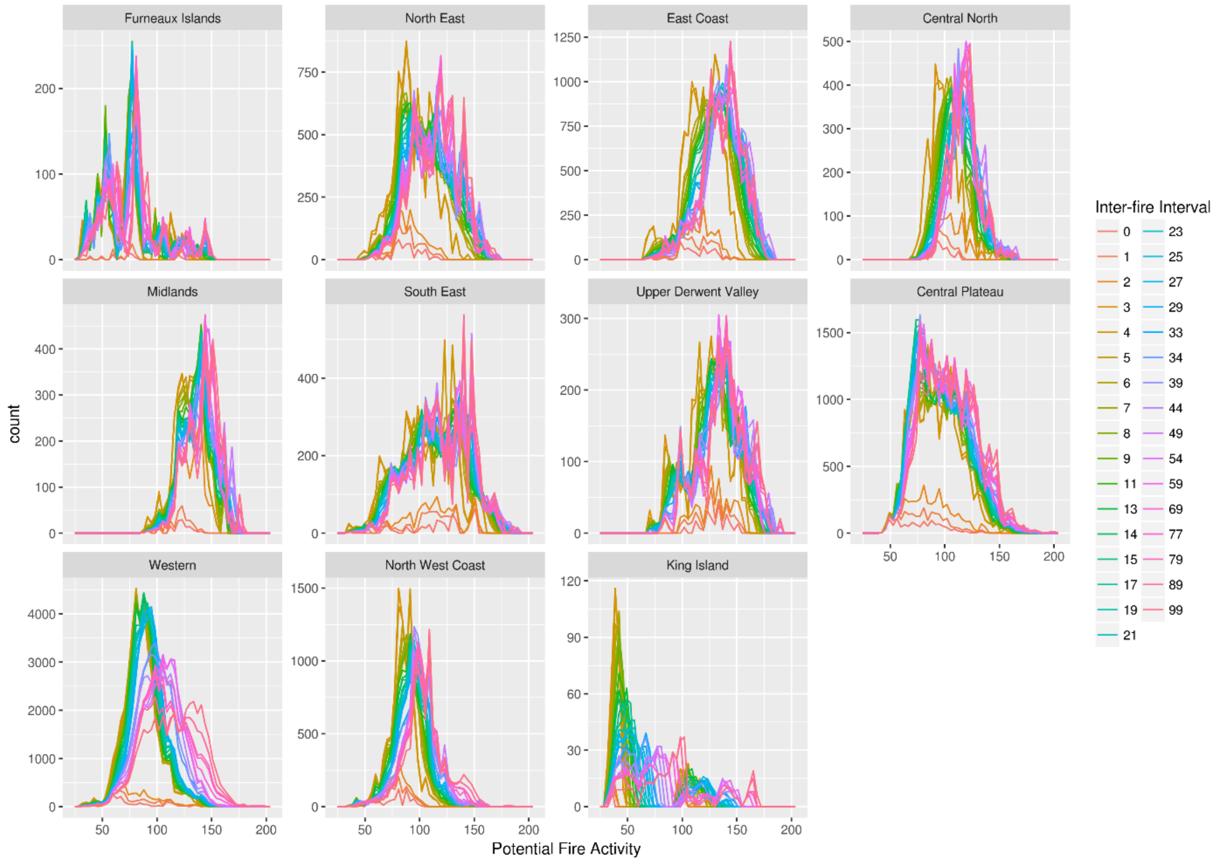

Figure 3.8: Impact of fire interval on Potential Future Fire Activity in the Bureau of Meteorology forecast districts.

3.3.3 Impact of fire frequency on treatability

Untreatable vegetation types, such as alpine and subalpine heathland and grasslands and rainforest, are excluded from fuel management because their sensitivity to fire would result in the loss of fire-sensitive species and long-term changes to their composition. Table 3.4 lists the vegetation types considered treatable in fuel management guidelines.

At fire intervals of between 5 and 50 years, there is little change in the percentage treatability across Tasmania over the time periods, from the baseline to end of century, within each fire frequency (Figure 3.9). Intervals of less than 5 years maintain the highest proportion of vegetation requiring fuel management. The reduction in treatability requirements at very high frequencies reflects the shift to the bare ground state of fire-sensitive vegetation types over time. At very long fire intervals, the percentage of treatable vegetation drops over time because in the absence of fire, vegetation transitions to wetter forest types.

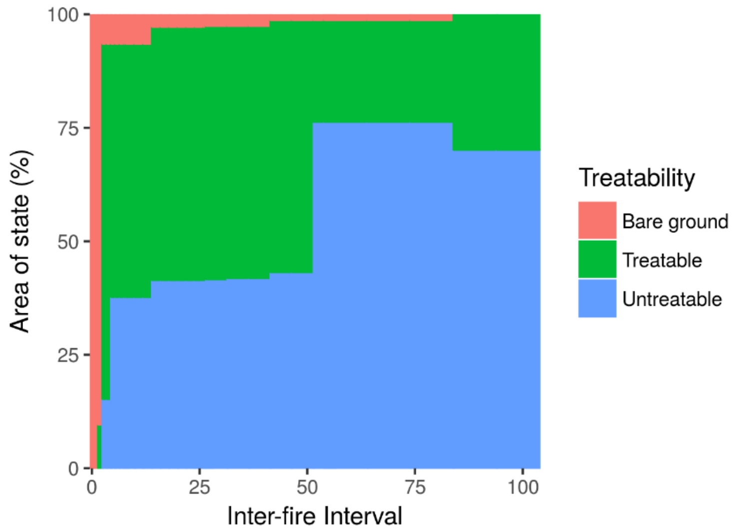

Figure 3.9: The impact of fire interval on the area of the state requiring fuel management.

3.3.4 Discussion

Future fire danger is projected to increase substantially under ongoing climate change (Fox-Hughes et al. 2014; Fox–Hughes et al. 2015, and above). More frequent bushfires can therefore be expected, leading to a greater need for prescribed burning to reduce bushfire risks. However, trade-offs will occur between fuel reduction and vegetation transitions in response to more frequent fire. The vegetation pathway model is a tool to illustrate the potential impacts of a dryer and warmer future climate in combination with management decisions about the frequency of prescribed burning. Within the model, ecological theory is translated into visualizations and summaries of potential landscape-scale change, to consider the impact of fire frequency on vegetation type, potential future fire activity, and the consequences of such changes for the proportion of a region that will require fuel management.

Currently, prescribed burning is applied in Tasmania for fuel reduction, ecological management, and weed control purposes (Marsden-Smedley 2009). Each of these objectives requires different intensities and frequencies of burning, which also vary in different vegetation types. In asset protection zones, fires of sufficient intensity are required to reduce the fuel load while ensuring that safety standards are not compromised and fires can be contained. Except in cases where the asset is a fire-sensitive species or community, there is a trade-off in these zones between fire risk reduction and ecological impacts. Broad-scale fuel management is then applied in strategic management zones to increase the potential to suppress bushfires and reduce wildfire size, whilst aiming to minimize adverse impacts on other values. In ecological management zones, fires may be suppressed, or prescribed burning applied at a range of intensities and frequencies appropriate for the target species or community, so that a mosaic of burnt and unburnt areas is maintained. The aim in these zones is that no vegetation transition should occur as a result of fire management.

Fire frequency has a substantial impact on the future Potential Fire Activity (PFA) relative to the impact of the changing climate over the coming decades. While the climate is projected to become warmer and drier over time, leading to higher fire danger, fire frequency is the dominant driver of future fire activity because of the feedback between fire and flammability in drier, fire-adapted vegetation types. Frequent fire has the potential to lead to shifts in vegetation type, away from mesic, fire-sensitive types, towards drier, more fire-adapted vegetation. The rate of change differs across the vegetation types, with some fire-sensitive communities irreversibly impacted by even a single fire and requiring very long recovery times. For example, rainforest communities with conifers may never recover after a fire, as *Athrotaxis* is an extremely slow growing and very long-lived tree that is killed by fire. In such communities, there is a positive feedback where fires promote vegetation that is more flammable, increasing the risk of fire. In contrast, fire-adapted vegetation such as dry eucalypt forests recover relatively quickly after fire and are only impacted by very frequent fires.

The percentage of land that is treatable, requiring consideration of prescribed burning to fulfil operational requirements has important implications for resource allocation and planning. Fire intervals of less than 5 years maintain the highest proportion of vegetation requiring fuel management across Tasmania. A drop in treatability over time can be achieved either by maintaining very high frequencies (less than 3 years), which result in the shift to the bare ground state of fire-sensitive vegetation types over time, or very long fire intervals (more than 30 years), because in the absence of fire, vegetation transitions to wetter forest types in the model. However, the latter is an unrealistic scenario requiring active fire suppression in the very long term. The challenge of suppressing fires even at relatively small scales is already becoming evident in Tasmania, as shown by the impact of recent fires in The Tasmanian Wilderness World Heritage Area. This area contains the core refugium of the paleo-endemic conifer *Athrotaxis cupressoides,* a species restricted to cool, wet climates and fire-free environments. Following an extremely hot and dry summer in 2015/2016, a lightning storm ignited numerous fires which burnt large stands of *A. cupressoides* (Harris et al. In Press, Fox-Hughes et al, 2015). Recovery is unlikely because of the species' slow growth and limited seedling establishment and the positive feedback between fire and flammability discussed above. Fire suppression is likely to become increasingly difficult in the future as fire danger increases, the fire season becomes longer and the window available for prescribed burning narrows under ongoing climate change.

We have presented state-wide results, but similar assessments could be generated for any subregion and will reflect the different vegetation types within the region of interest. The percentage of vegetation requiring fuel treatment is likely to differ across different districts depending on the vegetation types present, as they follow different transition pathways. Further exploration of the changes within a region, or particular forest, would be useful to inform conversations about the range of possible futures under different fuel management strategies.

The pathway approach is a useful tool for assisting community adaptation, by illustrating the potential impacts of a dryer and warmer future in combination with decisions seeking to manage fire risk in the future. Change over time under different scenarios of fire frequency can be spatially represented to show the shifts in vegetation type across the landscape and, hence, flammability. Maps can be used to show the distribution of the different vegetation types across the landscape, and how this changes at different fire intervals. The regions with the most fire-sensitive vegetation types and, therefore, greatest potential for vegetation transitions can be highlighted in this way to improve understanding of the tradeoffs between conservation, flammability, and fuel management.

The model involves a considerable simplification of the real world of vegetation and fire at the landscape scale. Flammability and fire sensitivity, for instance, are categorized into four and five classes, respectively. We have based these classes on available research in Tasmania, but any number of classes could be incorporated. Recently logged wet eucalypt forest and rainforest, for example, might be better represented by an additional flammability class, because the increased exposure of the understorey to insolation and altered floristics leads to higher flammability compared to undisturbed forests. More refined categories, based on understandings of the many fuel characteristics that influence fire, could be incorporated to make the model more regionally specific.

3.3.5 Further developments

There are several factors influencing fire activity that could be included in the model with further development. Aspect could be incorporated to consider its influence on fire intensity and frequency, through temperature and drying effects and differential fire spread. Moderate resolution imaging spectroradiometer (MODIS) canopy cover class could be used to distinguish different canopy cover within the broad vegetation types and within mapping units (e.g., “forest” and “woodland” canopy structure; recently logged or cleared vegetation). However, some factors such as forest growth under elevated CO_2 are unable to be projected into the future because of lack of knowledge or complex interactions and feedbacks (summarized in Harris et al., 2016). Other improvements would require targeted empirical research to increase understanding of fire intensity across vegetation types; improve accumulation curves across a range of vegetation and geological types; and include variations in ignitions and fire size, informed by fire history. These developments would better reflect the mosaic of burnt and unburnt areas that is maintained by the fire agencies within the different management zones (e.g., asset protection, ecological, and strategic management zones).

Further work is also necessary to incorporate changes to vegetation composition over time due to changing climate suitability. While we expect that vegetation change will occur slowly over long timeframes in the forest types because of the longevity of the dominant species, vegetation change may be more rapid in the alpine and subalpine regions, where the suitable climate is projected to constrict over the coming decades as Tasmania becomes warmer and drier. Additionally, extreme events such as heatwaves and droughts may cause sudden shifts in the vegetation in these regions, where the dominant species are less resilient to extremely high temperatures and/or low moisture conditions. Similarly, the distribution of vegetation types in which structurally important species have particular climatic requirements (e.g., *Athrotaxis*) may change over time.

The transitions in the model are based on the assumption of low to moderate fire intensity such as might be applied in asset protection zones and in some areas within strategic management zones. They do not capture the impact of very high-intensity, high-severity fires that can sometimes lead to immediate change after a single fire. The occurrence of such fires is likely to increase in the future as lightning ignitions and fire danger increase. Additionally, we have assumed that vegetation responses will remain the same under future climate conditions, but this may not be the case as vegetation becomes stressed by ongoing climate changes such as droughts. For example, dry eucalypt forests, which in the past have recovered relatively quickly after fire, may become more vulnerable to transition due to the cumulative effect of drought.

3.4. Conclusions

Fire frequency has a large impact on future fire activity relative to the impact of the changing climate over the coming decades. Frequent fire has the potential to lead to shifts in vegetation type, away from mesic, fire-sensitive types, towards drier, more fire-adapted vegetation. This leads to a positive feedback between fire and flammability in drier, fire-adapted vegetation types. The rate of change differs across vegetation types, leading to changes in vegetation structure and flammability at the landscape scale. The pathway model consolidates current understanding in the field into an interactive framework, enabling plausible futures to be explored. It could be used as a tool in community adaptation, to frame potential futures and identify the consequences of decisions seeking to manage fire risk in the future. Change over time, under different management regimes (frequency of prescribed burning), can be spatially represented to show the shifts in vegetation types across the landscape. Further model development is required to incorporate the interactions between fire intensity and prescribed burning and changes to vegetation composition over time due to changing climate suitability.

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Appendix 3 – Potential Fire Activity calculations

Modelling "Potential Fire Activity" (PFA) is a two-step process. First, the broad vegetation type is determined for each cell for a particular time and inter fire interval. Then, the PFA is calculated at each grid cell (10 km) across Tasmania, Australia, using the appropriate attributes for that type, following the equation:

$$\text{Potential Fire Activity (PFA)} = \text{Biomass} + \text{Availability to Burn} + \text{Fire Weather} \qquad (1)$$

where Biomass = (productivity × fuel load at time since fire); Availability to Burn = flammability of vegetation type at current Soil Dryness Index (SDI) × slope factor; and Fire Weather = Fire Danger Index (FFDI or MFDI, depending on vegetation type).

Each term is described in detail below.

A3.1. Biomass

There are two components to the Biomass term: productivity and the fuel load.

A3.1.1. Productivity

The GROCLIM sub-model from the ANUCLIM model (Hutchinson 2011) was used to generate an index of relative potential plant growth, based on plant growth response to light, temperature and water regimes under current and future climate conditions. While the growth index does not represent actual biomass production, it is a useful index to characterise plant production potential across the landscape.

Annual mean growth indices were computed for three thermal types using a parabolic thermal response curve (because of the C3 photosynthetic pathway), and the optimum temperature and thermal ranges shown in Table A3.1. The C3-Mesotherm plant type has a relatively broad range of growing degree temperature (3-36°C) with an optimum temperature of 19°C and is most applicable to temperate species. The C3-Microtherm plant type has a range of growing degree temperature from 0-20°C with an optimum temperature of 10°C, so is most applicable to conifers and cool to cold temperate climate plants. An additional GROCLIM index was customised to represent forest growth, based on the known thermal requirements of *E.globulus* (T_{min} 8°C, T_{max} 40°C, T_{opt} 16°C) (Sands and Landsberg 2002). The growth index is a dimensionless index with a scale of zero to one, where plant growth is minimal or non-existent below a growth index value of 0.2. This was scaled by multiplying by 1.6, so that productivity could increase or decrease under future conditions of temperature and rainfall.

A composite GROCLIM layer was calculated for each time period, with the appropriate GROCLIM thermal types applied to each broad vegetation type, as follows. The C3-Microtherm index was used for all areas with alpine and subalpine vegetation types, Buttongrass (because generally at altitudes >600m in colder regions), and Rainforest with conifers or deciduous beech (because of presence of conifers). The index based on the *Eucalyptus* thermal type was applied to all areas with Eucalypt forest types, and the C3-Mesotherm index was applied to all other regions to incorporate the broad thermal range of temperate plants in general.

Table A3.1: Parameters for plant types used in GROCLIM

Plant Thermal Regime	**Optimum temperature (°C)**	**Range (°C)**
C3 Micro	**10**	**0-20**
C3 Meso	**19**	**3-36**
Eucalyptus globulus	**16**	**8-40**

A3.1.2. Fuel load

The fuel load was calculated for each broad vegetation type at each time step, using the equation:

Biomass (of fuel) = L*(1-exp(-k*A)), where: L = carrying capacity
k = growth rate
A = age (or time since fire)

The values for carrying capacity and growth rate in Tasmanian vegetation types were decided on after consultation with the literature and fire ecologists (Jon Marsden-Smedley, Dave Taylor), and resulted in accumulation curves as shown in Figure A3.1. The value for the TasVeg type that made up the greatest area of each Broad Vegetation Type was used. These values can be updated as empirical data become available that better represent the productivity of different vegetation types on a range of soil types.

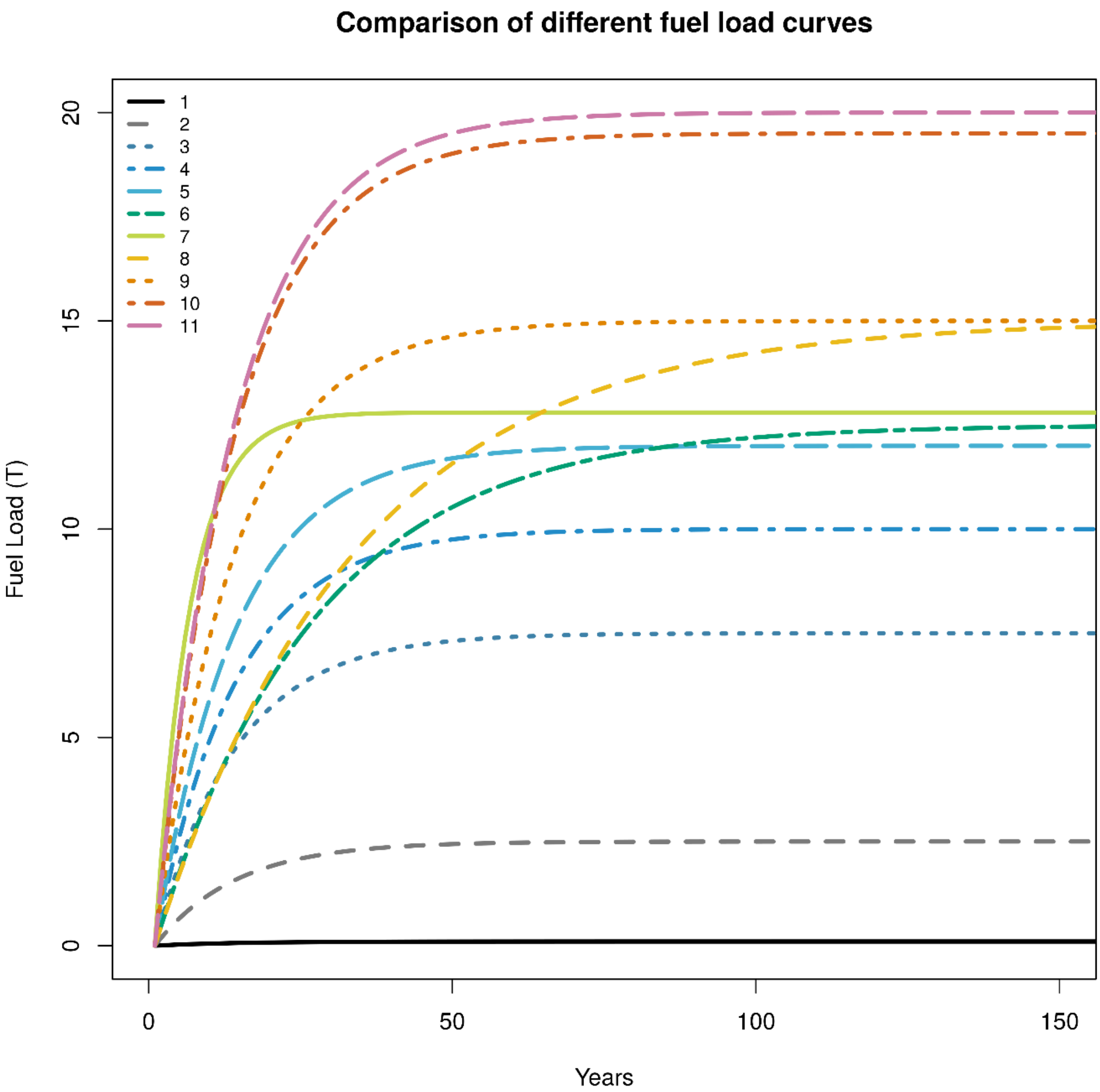

Figure A3.1: Fuel load versus time since fire in the broad vegetation types. The vegetation types associated with each curve are shown in Table A3.2.

Table A3.2: The vegetation types in the model associated with each fuel accumulation curve. Note that each type represents the different transition pathways that the current vegetation can follow, rather than an existing vegetation type.

1. "Bare ground"
2. Subalpine woodland
3. Eucalypt dry sclerophyll forest shrubby/ heathy/ grassy understorey
4. Alpine heathland with conifers
5. Alpine rushland/sedgeland; Buttongrass moorland woodland shrubby or heathy understorey, Buttongrass moorland, Eucalypt woodland shrubby or heathy understorey, Eucalypt woodland grassy understorey, Eucalypt grassland, Generic heathland grassland, Generic woodland shrubby or heathy understorey, Generic woodland grassy understorey, Generic grassland, Non-eucalypt grassland, Rainforest sedgeland, Rainforest grassland, Sphagnum sedgeland, Subalpine sedgeland, Subalpine grassland
6. Rainforest with conifers or deciduous beech; Rainforest without conifers or deciduous beech
7. Eucalypt dry sclerophyll forest shrubby or heathy understorey
8. Non-eucalypt wet scrub shrubby/heathy/sedgey understorey; Non-eucalypt wet scrub understorey, Rainforest wet scrub shrubby/ heathy/ sedgey understorey
9. Alpine heathland without conifers; Eucalypt dry sclerophyll forest shrubby/heathy/broadleaf/ grassy understorey; Generic forest; Non-eucalypt dry forest; Non-eucalypt dry scrub; Subalpine scrub; Subalpine heathland
10. Eucalypt wet sclerophyll forest with rainforest/ broadleaf/ shrubby/ heathy understorey; Non-eucalypt wet forest broadleaf/ shrubby/ heathy/ sedgey understorey; Subalpine rainforest
11. Generic heathland, Generic dry scrub, Non-eucalypt heathland, Rainforest heathland

A3.2. Availability to burn

This term of the Potential Fire Activity equation incorporates the Flammability of the vegetation type and a measure of fuel dryness, the Soil Dryness Index (SDI).

A3.2.1. Flammability

The four flammability categories (low, moderate, high and very high) are based on knowledge of the dynamics of fuel dryness for each vegetation type, which affects how many days per year the vegetation type will burn. Flammability is comparable to the classification of vegetation communities into 'fuel groups' in fire management plans in New South Wales and the national Bushfire Fuel Classification. The categories are defined in Table 3.1.

As with fire sensitivity, the flammability category was changed at each time step to reflect any changes to vegetation type.

A3.2.2. Soil Dryness Index (SDI)

The Soil Dryness Index (SDI) was used to predict the relative flammability of different vegetation types at future time periods (Table A3.3). The SDI is a measure of soil moisture and can be used as an index of fuel moisture (coarse woody fuels). An overview of the SDI and its strengths and weaknesses can be found in Marsden-Smedley (2009).

A3.2.3. Slope Factor

The slope of the land has a direct effect on fuel pre-heating and wind speed, so a slope correction factor was applied to each pixel, following the BRAM – Bushfire Risk Assessment Model (Parks and Wildlife Service). Slopes > 31% were weighted by 10; slopes 21-30% by 5; slopes 16-20% by 3; and slopes 0- 10% were weighted by 1.

A3.3. Fire Weather (FFDI, MFDI)

Two different fire danger indices were used to indicate fire weather at each time period. Both indices incorporate surface air temperature, relative humidity and wind speed, combined with an estimate of fuel dryness (Drought Factor, based on Soil Dryness Index and recent precipitation) to give an index of daily fire danger. The Moorland Fire Danger Index (MFDI) was used for areas with Buttongrass Moorland, Sphagnum and Sedgeland vegetation. This index is better suited to moorlands and other types where soil dryness has less of an influence on fire behaviour. The annual cumulative MacArthur's Forest Fire Danger Index (FFDI) was applied for all other vegetation types, although it may not adequately represent fire danger in Heathland and Scrub vegetation types.

Table A3.3: Flammability at different levels of Soil Dryness Index (SDI), from Marsden-Smedley (2009).

Soil Dryness Index	**Broad Vegetation Type**	**Flammability**
≤10	**Buttongrass moorland**	**High**
	Wet scrub, dry eucalypt forest	**Very low**
	All other types	**Non-flammable**
11-15	**Buttongrass moorland**	**Very high**
	Wet scrub, dry eucalypt forest	**Low**
	Wet eucalypt forest	**Very low**
	Rainforest	**Non-flammable**
16-25	**Buttongrass moorland**	**Very high**
	Wet scrub	**High**
	Dry eucalypt forest, Wet eucalypt forest	**Moderate**
	Rainforest	**Non-flammable**
26-50	**Buttongrass moorland**	**Very high**
	Wet scrub, Dry eucalypt forest	**High**
	Wet eucalypt forest	**Moderate**
	Rainforest	**Low**
	Buttongrass moorland, Wet scrub, Dry eucalypt forest	**Very high**
>50	**Wet eucalypt forest**	**High**
	Rainforest	**Moderate**