# *Comparing Observed and Projected Changes in Australian Fire Climates*

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# Comparing Observed and Projected Changes in Australian Fire Climates

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**Abstract:** The Forest Fire Danger Index (FFDI) is the main measure used in Australia for estimating fire risk. Recent work by the authors showed that the FFDI forms stable state regimes, nominated as fire climate regimes. These regimes shifted to greater intensity in southern and eastern Australia around the year 2000 and, a decade later, further north. Reductions in atmospheric moisture were the primary contributor. These changes have not been fully incorporated into future projections. This paper compares the recent regime shifts with the most recent national projections of FFDI, published in 2015. They show that for most states and regions, the 2030 upper limit is approached or exceeded by the recent shift, except for two states with large arid zones, South Australia and Western Australia. Methods for attributing past changes, constructing projections, and the inability of climate models to reproduce the recent decreases in atmospheric moisture, all contribute to these underestimates. To address these shortcomings, we make some suggestions to modify efforts aiming to develop seamless predictions and projections of future fire risk.

**Keywords:** fire climates; pyroclimates; regime shifts; Forest Fire Danger Index; climate projections; Australia



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## 1. Introduction

Fire climate regimes shifted in most regions of Australia around the year 2000 or a decade later [1]. Attribution of those changes showed that reductions in relative humidity (RH) and increased fire season maximum temperature (Tmax) were the main contributing factors [1]. Other work has identified that downward shifts in relative humidity have occurred globally and regionally over the past two decades [2]. These reductions are routinely underestimated by climate models [2–4].

These changes in fire climate regimes have been noted by fire managers and are evidenced by increases in areas burned, declarations of catastrophic or "code red" conditions and the incidence of fire-generated pyrocumulonimbus [5–7]. This is despite ongoing improvements in prediction, protection and response. Of interest then, are how these changes compare with projections of future fire weather.

In Australia, McArthur's Forest Fire Danger Index (FFDI) [8–10] has been the main measure of fire weather, both for estimating historical changes and future projections. We defined a fire climate (pyroclimate) as the incoming climate external to a region that affects the propensity for wildfire to occur [1]. Historically, fire climate regimes represented by FFDI remained relatively stable from 1957 until the regime shifts noted above.

Future projections of FFDI have been produced since 2005, covering SE Australia [11–14] and the nation [15,16]. Climate model-based studies for specific regions include a future fire danger climatology for Tasmania [17], projections for Victoria [18], New South Wales [14], and nationally [16]. The most recent national projections were carried out for Australia's natural resource management regions [15], utilizing the Clarke, et al. [19] historical data set.

Similar to many studies projecting future changes in climate, these studies have compared future changes in FFDI with a current baseline. Successive iterations produce more recent baselines as they are updated. Most studies applied a time-slice method, estimating changes for a future year with a range on either side to reduce uncertainty in the amount of change (e.g., 2030 ± 15 years). The presence of steady-state regimes offers the possibility of providing a physically-defined baseline, as opposed to a statistical baseline selected to represent current conditions.

The main aim of this paper is to compare and contrast recent regime shifts in fire climates for Australia with longer-term projections of the FFDI. Two measures of fire danger—the annual sum of fire danger index (ΣFFDI) and annual number of days of severe fire danger or above (Days Sev+)—are compared for recent climate baselines, the current fire climate regime with low and high climate projections for two future time periods (centered at 2030 and 2090), for eight regions of Australia. Most of these come from Climate Change in Australia (CCIA2015) [15], but we also compare the current regime shift with projections from other studies where possible. Finally, we discuss the ramifications of applying trends to nonlinear data and system climate model underestimation of changes in FFDI and explore the challenges of overcoming these limitations.

## 2. Materials and Methods

### 2.1. Baseline FFDI

Historical FFDI as used by the Australian Bureau of Meteorology (BoM) has been converted from the original metered measurements into the following equation by Noble, et al. [10]. The BoM uses the Lucas [20] formulation:

$$\text{FFDI} = 1.2753 \times \exp[0.987\ln(\text{DF}) + 0.0338\text{Tmax} + 0.0234\text{V} - 0.0345\text{RH}] \quad (1)$$

where DF is the drought factor, Tmax is the maximum temperature, V is the 3 p.m. windspeed, and RH is the 3 p.m. relative humidity. Inputs into the drought factor include the Keetch Byron Drought Index and rain days. FFD is an index originally calculated on a scale of 100 based on the 1939 Black Friday fires [8,9], but has more recently exceeded 100, with that level being categorized as catastrophic [12].

The baseline data for this study were constructed from a multivariate linear regression for FFDI constructed using high-quality climate data available from the Australian BoM climate tracker. The rationale for this approach is that windspeed and relative humidity lack long-term homogenous observations and are difficult to homogenize. The baseline data for that exercise were the Victorian average FFDI from seven stations from 1972–1973 to 2009–2010 adjusted for inhomogeneities. Fire years from July to June were used [1].

The multivariate linear regression applied the annual average rainfall anomaly (P), fire season maximum temperature (TmaxFS), the area exceeding the 90th percentile of Tmax, and the mean 3 p.m. cloud amount in oktas (0.8 maximum). The indices assessed were annual ΣFFDI and days above high (Days Hi+, >12), very high (Days VHi+, >25), and severe fire danger (Days Sev+, >50).

The results were compared with a 39-station data set compiled by Lucas and Harris [21,22] (4 stations in Victoria, LH2019). These covered a longer period (1971–2016) than the training data, allowing independent verification. Lucas and Harris produced median FFDI (MFFDI) which was compared with ΣFFDI and the 97th percentile FFDI (97FFDI) which was compared with Days VHi+. The Nash–Sutcliffe variable was good to very good for the FFDI comparisons and similar for P and Tmax (Table 1; ratings from Moriasi, et al. [23]). This is referred to as the HQD model for high-quality data.

These results gave us confidence that the HQD model could be applied more widely. The initial model was expanded to 1957–1958 to 2019–2020 for Victoria, the period where high-quality data were available, and subsequently applied to other states and regions. States and regions are shown in Figure 1.

**Table 1.** Nash–Sutcliffe efficiency coefficients for the pairs of MFFDI and ΣFFDI, and 97FFDI and Days VHi+, along with fire year total P and average Tmax for the regression model with the LH2019 average for Victoria. Reproduced from [1].

| Period | MFFDI/ΣFFDI | 97FFDI/Days VHi+ | P | Tmax |
|---|---|---|---|---|
| 1971−2016 | 0.88 | 0.79 | 0.82 | 0.93 |
| 2011−2016 | 0.95 | 0.85 | 0.88 | 0.97 |


**Figure 1.** States and regions of Australia analyzed in the assessment.

Verification of the results was subject to the distribution and quality of the station-based data from LH2019. Performance for Victoria, New South Wales, and SE Australia qualified as good to very good based on the Nash–Sutcliffe variable. Queensland and Northern Territory results were very good for ΣFFDI and satisfactory for Days Sev+, perhaps because arid to tropical climates are present in one region. South Australia was satisfactory, with stations biased to cooler and wetter areas. Western Australia was satisfactory for ΣFFDI only, with stations biased toward the coast. It is a large state with different fire climates. Tasmania was unsatisfactory due to the bias of stations toward the drier and warmer eastern side of the state. SW WA performed very poorly due to station location and data quality [1].

Our conclusion was that the regression provided a reliable annual climatology for FFDI for regional averages. In regions where station coverage is biased or poor, the HQD model will be more reliable in estimating historical change than using station averages [1]. That meant the HQD model data could serve as a reliable baseline for comparison with projections.

### *2.2. Measuring Regime Shifts*

The HQD FFDI time series 1957–2021 were then analyzed for regime shifts for each region and index [1]. Testing was conducted using the Maronna–Yohai [24] bivariate test. This test has been widely used to detect inhomogeneities in climate variables [25–28], decadal regime shifts in climate-related data, and step changes in a wide range of climatic time series [29–33]. A full technical description of the test can be found in Jones and

Ricketts [34]. Note that the bivariate test contributed to both inhomogeneity assessment and regime shifts in this project.

From 1995–1996, fire climate regimes began to shift in fire-prone areas of Australia, starting in Victoria and Tasmania and expanding west to South Australia, SW Western Australia and Western Australia, and north to New South Wales through to 2002–2003. Queensland shifted a decade later and potentially the Northern Territory over the period 2011–2017, but $p$-values for the latter were inconclusive. The initial regime from 1957 is labeled Regime 1 and the new state Regime 2. A full description of the methods and results is in [1], with details in the SI.

### *2.3. FFDI Projections*

The most recent national projections (CCIA2015) were conducted for Australia's eight natural resource management regions [15]. These regions are not congruent with state boundaries, but data were provided for 36 individual stations. These were averaged across each state and region. The results shared 35 stations with the LH2019 data, allowing their reliability for each region to be estimated.

CCIA2015 presented results for two FFD indices: ΣFFDI and Days Sev+. Three climate model results—CESM, GFDL, and MIROC were provided, using two greenhouse futures—RCP4.5 and RCP8.5. Also supplied were changes in mean annual P, Tmax, and the drought factor from the FFDI. The latter was not used. The baseline from which changes were measured was 1981–2010 with a midpoint of 1995.

Projections for two time slices were provided, centered on 2030 (2016–2045) and 2090 (2076–2105). For the two greenhouse futures and three models, the lowest and highest estimates for 2030 and 2090 were calculated for each state and region except the Northern Territory, which only had one station in CCIA2015. Changes were measured as the difference from the 1981–2010 fire years.

To provide an idea as to how baselines have changed, we have included the two baseline periods from Lucas07 [12] and CCIA2015 [15]. Each baseline was estimated from the HQD FFDI data calculated for this project: 1972–1973 to 2006–2007 for Lucas07 and 1981–1982 to 2010–2011 for CCIA2015, respectively. The data used are in the Supplementary Materials.

We also compared the results with individual studies where possible. Necessary adjustments were made to ensure that comparisons between regimes, baselines, and projections were compatible. As each study required different treatments, the details of those accompany the results.

## 3. Results

### *3.1. Nationwide Comparisons*

This section compares the Lucas07 and CCIA2015 baselines, and regimes 1 and 2 with the current regime and future projections for 2030 and 2090 for each state and selected regions. The baselines show an upward trajectory for Regime 1 to Lucas07 and CCIA2015, each extending further into the new regime.

Figure 2 shows low and high projections for 2030 and 2090 for ΣFFDI. Ranges of change are larger for regions with substantial arid zones. This is because such areas usually have existing high fire danger and are very sensitive to proportional changes from model projections [35].

For Days Sev+ in Figure 3, the pattern is similar. Queensland, SW Western Australia, SE Australia, and New South Wales are all close to the upper limit for 2030 (in descending order). Victoria is midway, and South and Western Australia are nearer the lower limit. Tasmania is not included because of data limitations, but eastern Tasmania is known to experience severe fire weather. Only for Western Australia does Regime 2 not exceed the lower limit for 2090.

Regime 2 for Tasmania, SW Western Australia, SE Australia, and Queensland are all close to the upper limit for 2030. Victoria and New South Wales are about halfway up the 2030 range. South Australia and Western Australia are closer to the lower limit, and South Australia is partway up the range, but it has the largest projected uncertainties of all the states.

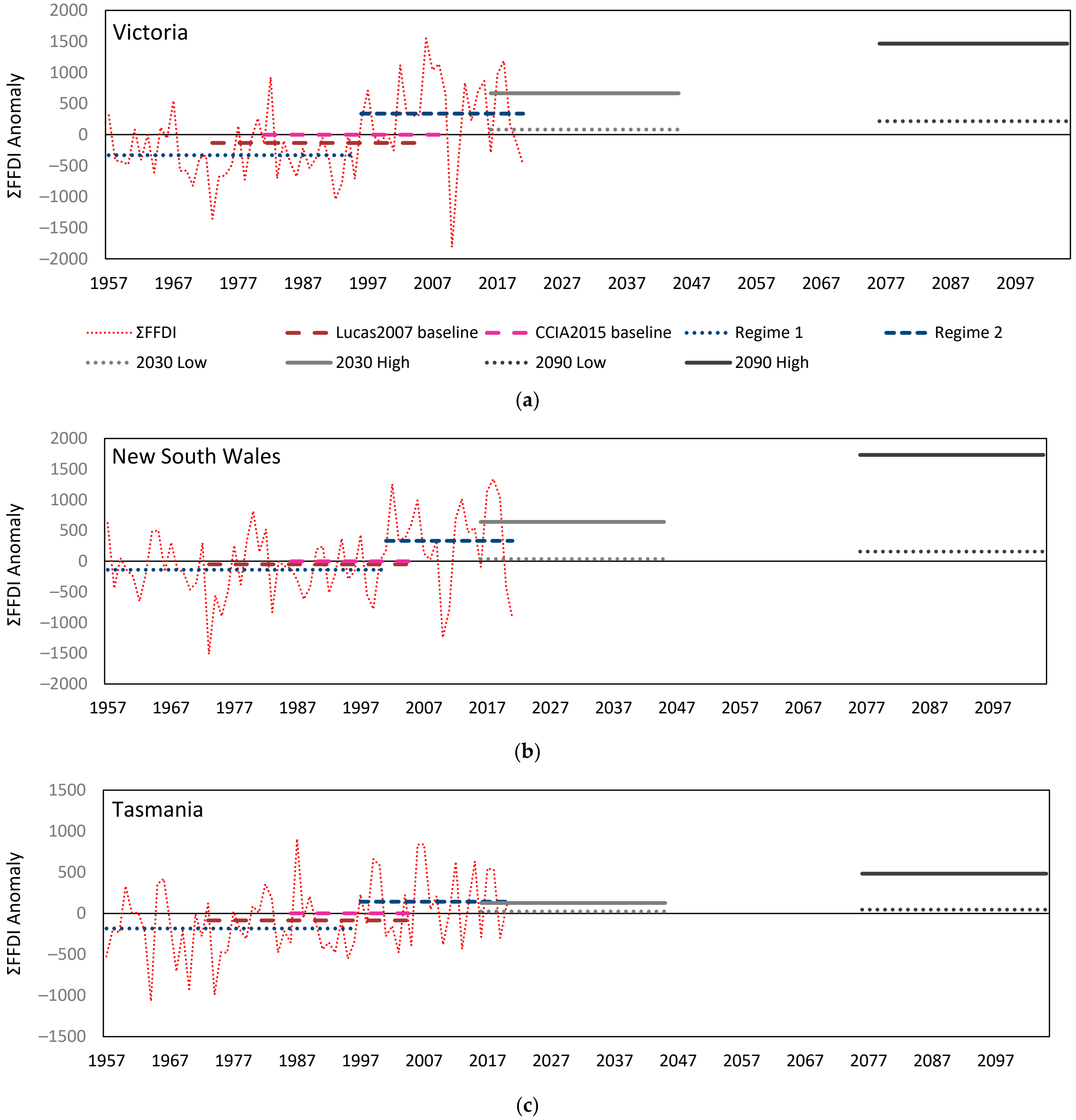
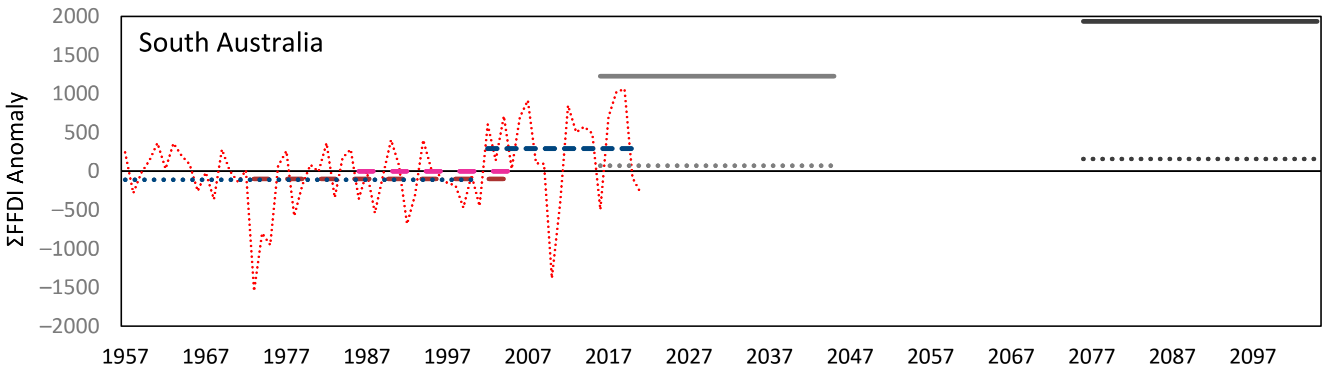



**Figure 2.** *Cont*.

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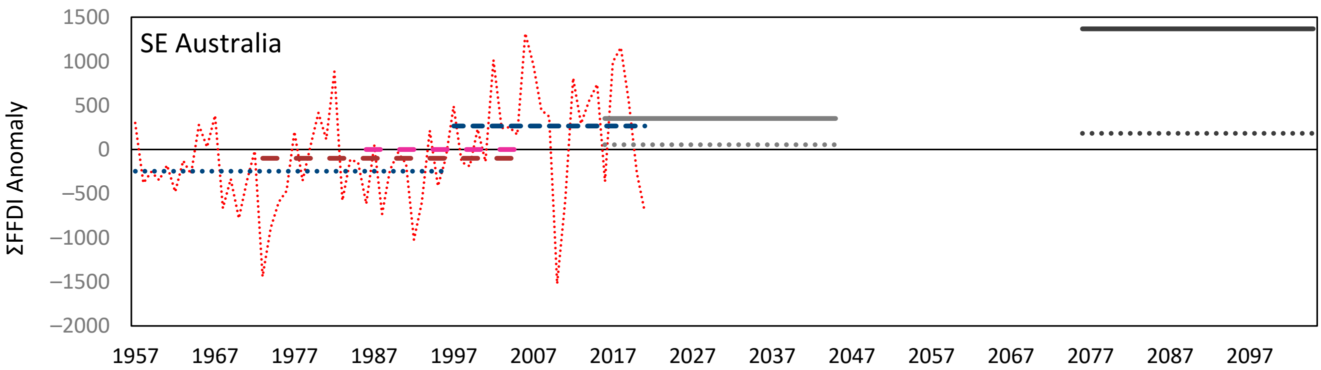


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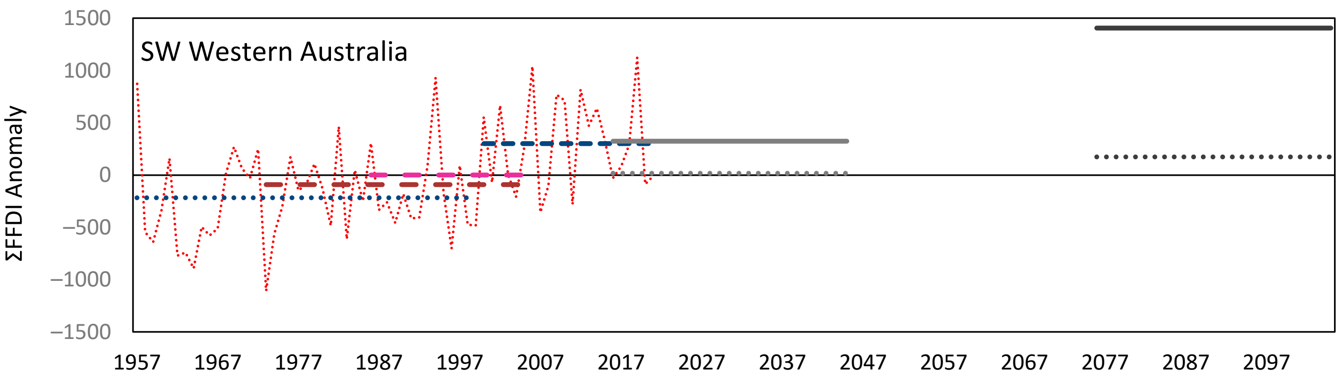


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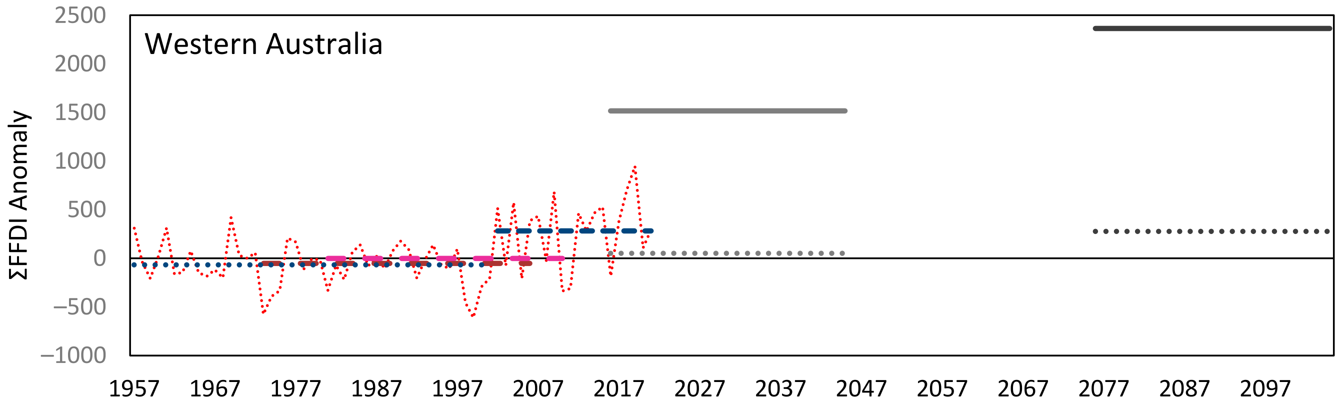


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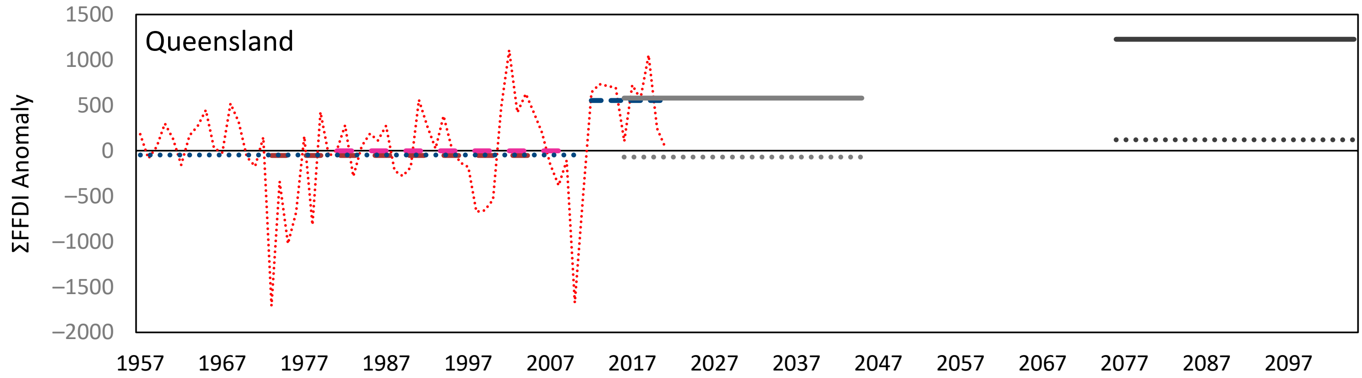
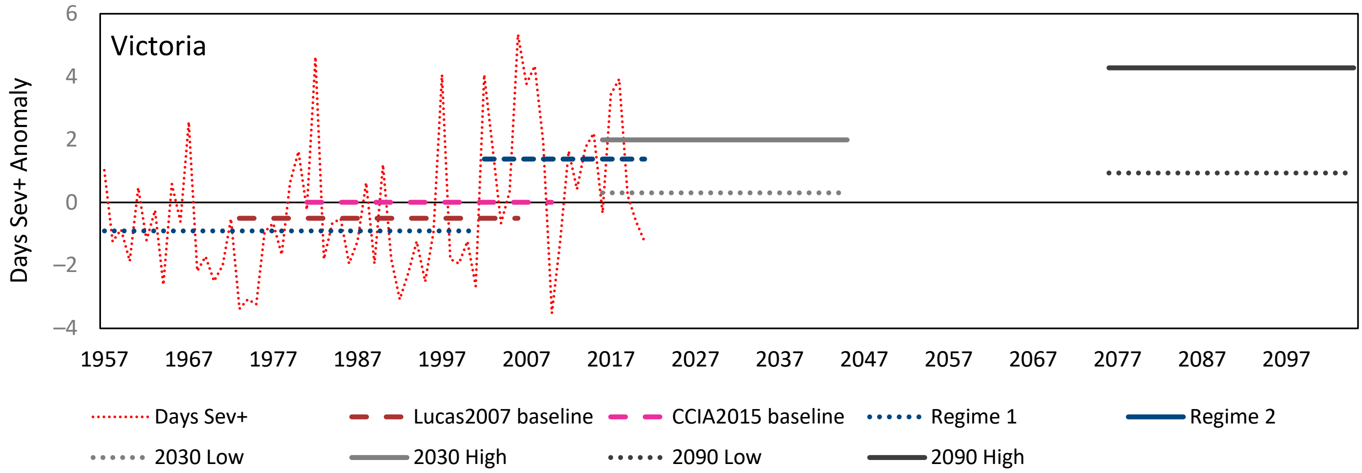



(**h**)

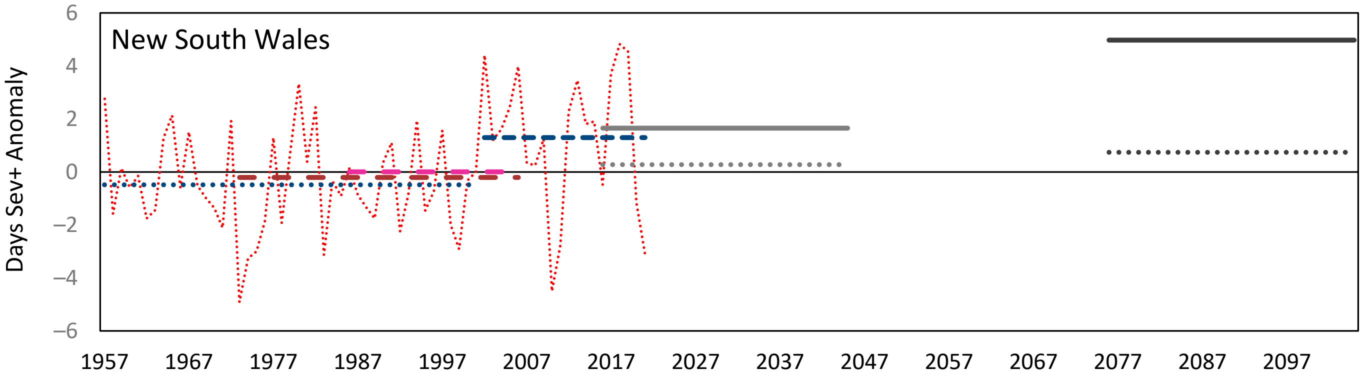
**Figure 2.** HQD ΣFFDI anomalies set to the baseline 1980–1981 to 2009–2010 (CCIA2015) offset by six months, magenta dashed line) showing the baseline 1972–1973 to 2006–2007 (Lucas07, brown dashed line) and most recent regime (dark blue dashed line), shown with the 2030 projected range of change (mid grey lines) and 2090 (dark grey lines) for (**a**) Victoria, (**b**) New South Wales, (**c**) South Australia, (**d**) Tasmania, (**e**) SE Australia, (**f**) SW Western Australia, (**g**) Western Australia, and (**h**) Queensland.

For some states and regions, changes occurring around the year 2000 rival, and even slightly exceed the maximum projections for 2030. Putting that into perspective, regime shifts in much of southern and eastern Australia equaled or exceeded the maximum projected changes three decades before they were projected to occur.

Table 2 compares the Regime 2 anomaly from the 1981–2010 baseline with the 2030 and 2090 median estimates for ΣFFDI and Days Sev+. It shows similar patterns to Figures 2 and 3, but the median is exceeded for all states save South and Western Australia, and marginally, New South Wales. Regime 2 for Queensland is almost double the median estimate. For Days Sev+, the 2090 median has been met or exceeded for most of the southern and eastern states, with South and Western Australia having substantially larger projected changes.




(**a**)

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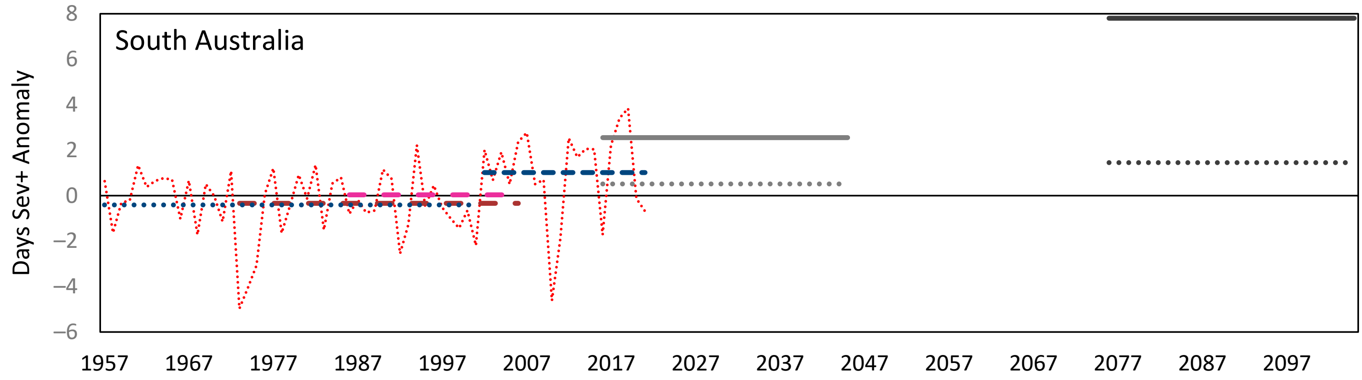


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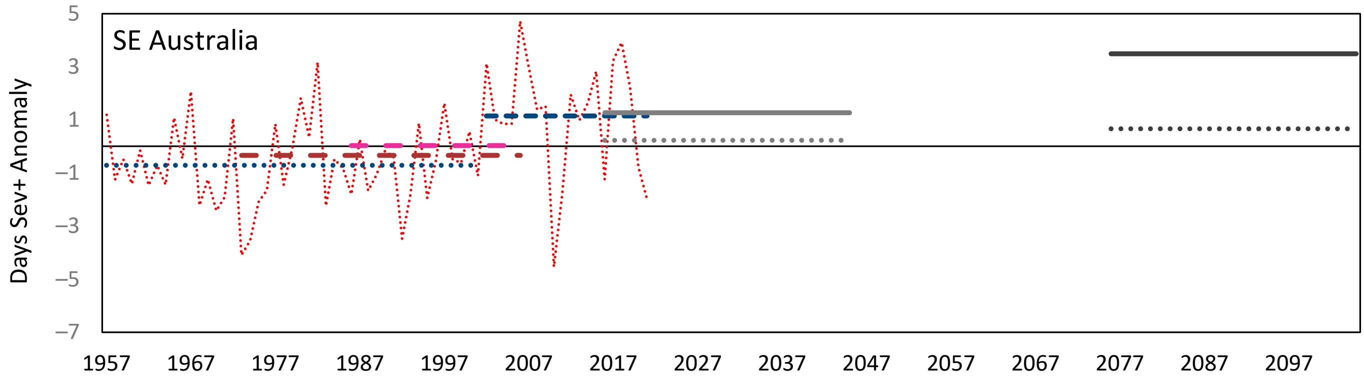
**Figure 3.** *Cont.*

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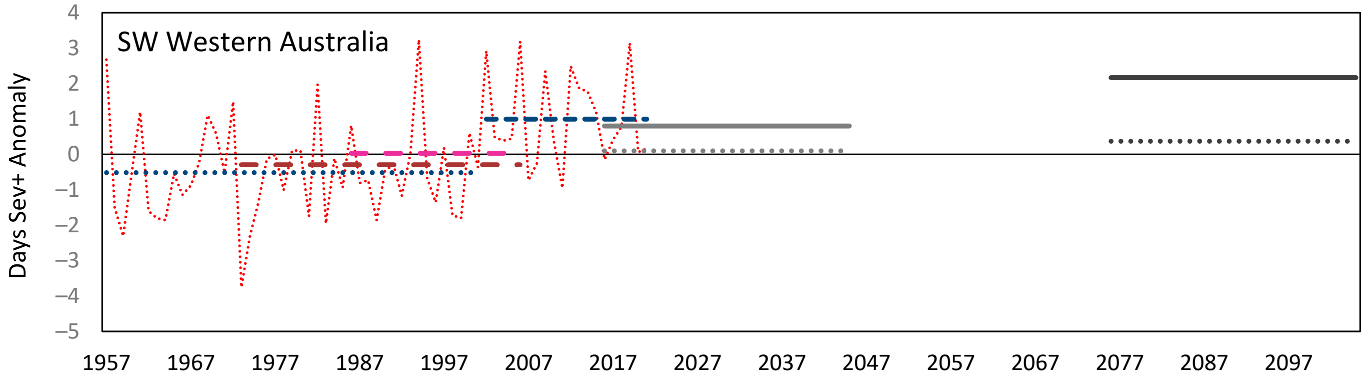


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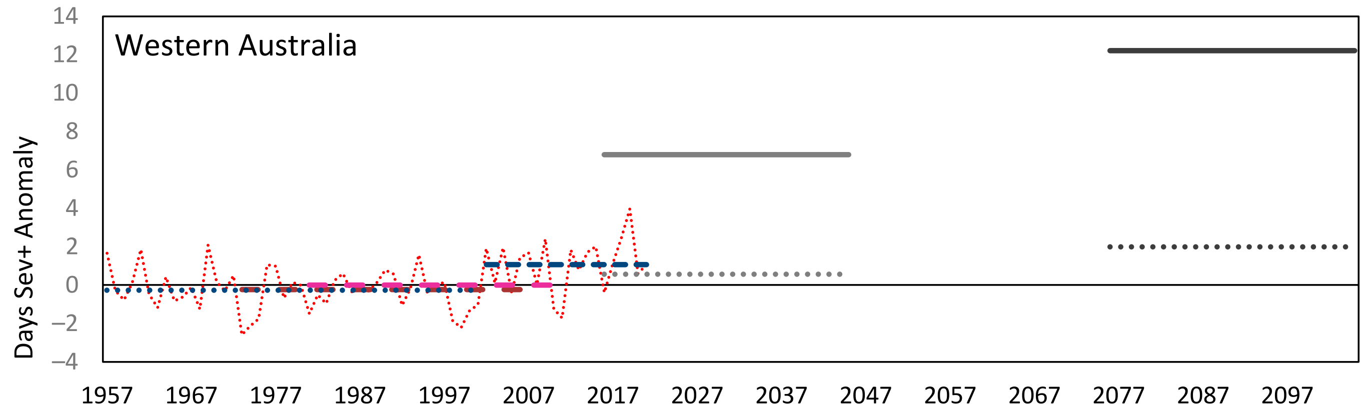


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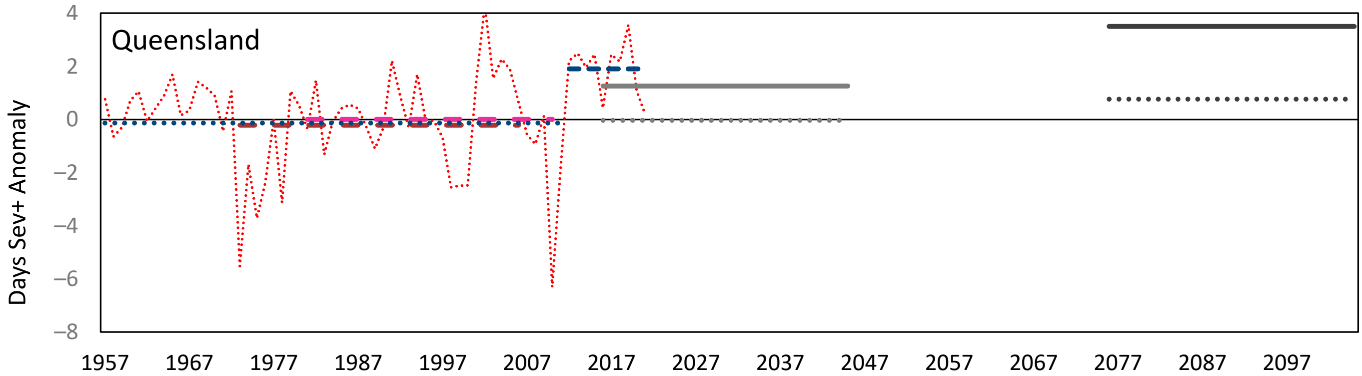
**Figure 3.** *Cont*.




**(g)**

**Figure 3.** HQD days Sev+ anomalies set to the baseline 1980–1981 to 2009–2010 (CCIA20151 offset by six months, magenta dashed line) showing the baseline 1972–1973 to 2006–2007 (Lucas07, brown dashed line) and most recent regime (dark blue dashed line), shown with the 2030 projected range of change (mid grey lines) and 2090 (dark grey lines) for (**a**) Victoria, (**b**) New South Wales, (**c**) South Australia, (**d**) SE Australia, (**e**) SW Western Australia, (**f**) Western Australia, and (**g**) Queensland.

**Table 2.** Difference between Regime 2, 2030, and 2090 median projections from the 1981–2010 baseline for ΣFFDI and Days Sev+.

| Region | ΣFFDI Regime 2 | ΣFFDI 2030 Median | ΣFFDI 2090 Median | Days Sev+ Regime 2 | Days Sev+ 2030 Median | Days Sev+ 2090 Median |
|---|---|---|---|---|---|---|
| Victoria | 339.3 | 243.5 | 360.4 | 1.0 | 0.7 | 1.2 |
| New South Wales | 333.5 | 344.8 | 437.4 | 1.3 | 0.9 | 1.2 |
| Tasmania | 141.0 | 84.0 | 209.0 | | | |
| South Australia | 292.6 | 362.0 | 444.9 | 1.0 | 1.5 | 2.2 |
| SW Western Australia | 302.2 | 211.7 | 447.5 | 1.0 | 0.3 | 1.0 |
| SE Australia | 266.9 | 231.2 | 335.4 | 1.1 | 0.5 | 0.9 |
| Queensland | 552.5 | 251.2 | 394.1 | 1.9 | 0.7 | 1.5 |
| Western Australia | 281.5 | 486.5 | 616.3 | 1.6 | 2.4 | 3.1 |

## *3.2. Comparisons with Regional Studies*

### 3.2.1. Victoria

Lucas, et al. [12] assessed future changes in FFDI across Australia, with six locations in Victoria common with the wind-adjusted set used to construct the HQD model, building on Hennessy, et al. [11] who assessed climate projections for SE Australia. Their study applied FFD indices. Table 3 compares Days VHi+ from both data sets using the 1973 to 2006–2007 baseline. Both average 19 days per year for Victoria. If the recent regime is taken as dating from 1996–1997, the changes from the baseline are approaching the high case for 2050. Clarke, et al. [19], analyzing the high-quality data set developed by Lucas [20] that extended to 2009–2010, also noted that recent changes rival future projections.

Lucas, et al. [12] also considered the return periods for catastrophic conditions. The worst case for 2050 is summarized in Table 3. They ranged from one every 10 years for Bendigo to 1.2 per year in Mildura. Some stations will be approaching this frequency, which is equivalent to once every 2.5 years when averaged over the state, but as discussed earlier, the short time series and data quality limit any confidence in return period results.

**Table 3.** Average number of Days VHi+ per year in FFDI for selected locations in Victoria from 1971–73 to 2006–07 from this report and Lucas, et al. [12] with 2020 and 2050 projections in percentages.

| Source | Melbourne | Laverton | Sale | Bendigo | Mildura | Mt Gambier | Victoria |
|---|---|---|---|---|---|---|---|
| This paper | 15.7 | 11.6 | 6.0 | 15.5 | 52.9 | 12.1 | 19 |
| Lucas 2007 | 14.8 | 11.8 | 5.4 | 13.9 | 56.6 | 11.5 | 19 |
| 1997–2010 | 22.7 | 15.1 | 8.6 | 28.9 | 77.2 | 15.5 | 28 |
| 1997–2010 (%) | 45 | 30 | 43 | 86 | 46 | 28 | 47 |
| 2020 low % | 6–7 | 2–4 | 1–7 | 12–16 | 5–7 | 1–3 | 5–7 |
| 2020 high % | 15–19 | 9–15 | 10–32 | 26–32 | 16–18 | 7–12 | 14–21 |
| 2050 low % | 9–12 | 5–9 | 18–50 | 20–13 | 10–13 | 5–7 | 11–32 |
| 2050 high % | 43–59 | 42–63 | 50–107 | 81–106 | 50–60 | 22–34 | 48–72 |
| Catastrophic 2050 highest | 0.4 | 0.4 | 0.2 | 0.1 | 1.2 | 0.2 | 0.4 |

Timbal, et al. [18] analyzed Melbourne, Laverton, Mildura, Sale, and Mt Gambier stations from 1972 to 2015, estimating an average linear trend change of 28% in ΣFFDI and 3.6 days in Sev+. This compares to 37% ΣFFDI and 3.2 Days Sev+ in the HQD model. They also estimated future changes, applying monthly mean factors to maximum temperature, rainfall, relative humidity, and wind speed to the CCIA2015 baseline from three climate models. Two forcing pathways were used: RCP4.5 and RCP8.5 [36]; both pathways were averaged for 2030 and presented separately for 2090. They estimated a state-average increase of 9.3% for ΣFFDI in 2030 and 14.1% and 34.4% for RCP4.5 and RCP8.5 in 2090, respectively. For Days Sev+, projections were 28%, 45%, and 120% in the same order. Regime 2 is close to the 2030 estimate for both indices and below the 2090 RCP4.5 estimate for 2090 (339 vs. 400 ΣFFDI and 1.0 vs. 1.7 Days Sev+).

Greater resources are being placed into the development of spatial climatologies, finer-scaled modeling, and statistical downscaling in order to improve the capacity to predict changes in fire risk. Clark, et al. [37] used the updated VicClim data set of fire weather and associated variables [38,39], including 32 atmospheric layers as the base climate and dynamically downscaled GCM data using coarse- and fine-scale synoptic reanalysis. The data downscaled were Tmax, RH, P, and horizontal 10 m wind speeds for the years 1973–2016 from the ACCESS 1.0 climate model.

They assessed bias using the daily 99th percentile FFDI from VicClim for the 44-year time series. These were generally underestimated, ranging up to −12 points, but were proportionally similar in coastal areas where FFDI is lower. The major contributing factors were windspeed on the plains, RH in hinterlands increasing to the NE, Tmax on coastal plains, and drought factor across the Great Dividing Ranges from west to east. Despite these drawbacks, they considered it a substantial improvement on existing techniques [37].

Clark, et al. [40] applied the same technique to downscale 12 models, projecting future changes for the RCP4.5 and RCP8.5 emissions pathways. RCP4.5 stabilizes emissions by 2100 and RCP8.5 is an extreme pathway where emissions continue to increase [41]. For the existing 44-year climatology, most models underestimated FFDI, while producing the overall pattern fairly well. Bias assessments showed that the largest contributors to these underestimates varied between models [40].

Changes for each pathway were assessed for 2045–2060 and 2085–2100 [40]. The results were presented in map form for the annual maximum FFDI ($FFDI_{max}$) and in Days VHi+ for five selected stations for RCP8.5. The ranges of change for $FFDI_{max}$ were greatest in the NW of the state, up to 15 points for RCP4.5 2045–2060 and 20 for RCP8.5 2045–2060. The latter exceeded RCP4.5 for 2085–2100. The increase was greater than 15 points for over half the state in RCP8.5 2085–2100. They more than doubled the baseline average in the NW with even greater relative increases in the cooler regions [40].

We analyzed $FFDI_{max}$ in the Victorian station data used for training the HQD model (it requires daily data) and did not detect any regime-like change. This measure is highly volatile, varying from very low in wet, cool years to very high in hot dry years. It is also highly clustered, so a single annual measure will not capture risk in the same way that days above a given threshold can.

Clark, et al. [40] also estimated percent change in Days VHi+ for RCP8.5 2045–2060 and 2085–2100 for five stations. These are compared with the shortened Regime 1 and 2 changes for the baseline record for Victoria (1972–2009) in Table 4. The difference between the 1972–2009 and 1973–2016 baseline periods for the Victorian HQD Days VHi+ is 1%, so a direct comparison is justified.

**Table 4.** Changes in days VHi+ (FFDI > 25) for the baseline data in this study (upper table) compared with the downscaled results average from 12 climate models for RCP8.5 2045–2060 and 2085–2100 [40]. For the upper table, Regime 1 is 1972–2001, Regime 2 is 2002–2009, and the baseline is 1972–2009. Columns in the lower table are matched with stations in the upper table having a similar climate. The baseline Days VHi+ for the five lower stations were estimated from a chart, but the percent changes were provided. Melbourne in the upper half is the urban regional office and Melbourne Airport in the lower half. Bairnsdale is between Sale and Orbost.

| | Melbourne | Laverton | Sale | Orbost | Omeo | Bendigo | Mildura | Nhill | Mt Gambier | State Average |
|---|---|---|---|---|---|---|---|---|---|---|
| 1972–2001 | 14 | 11 | 5 | 2 | 2 | 13 | 47 | 32 | 11 | 19 |
| 2002–2009 | 26 | 18 | 10 | 4 | 5 | 34 | 89 | 60 | 17 | 36 |
| Change | 81% | 65% | 78% | 87% | 154% | 171% | 88% | 85% | 50% | 89% |
| 1972–2009 | 17 | 12 | 6 | 3 | 3 | 17 | 56 | 38 | 12 | 23 |
| | | **Melb. Airport** | **Bairnsdale** | | | **Wangaratta** | **Walpeup** | | **Mortlake** | |
| 1973–2016 | | 12.5 | 3.5 | | | 17 | 58 | | 12 | |
| RCP8.5 2045–2060 | | 70% | 120% | | | 59% | 34% | | 40% | |
| RCP8.5 2085–2100 | | 117% | 216% | | | 103% | 65% | | 71% | |

The lower part of the table shows the Clark, et al. [40] baseline (1973–2016) and estimated future changes, with stations vertically lined up with the closest climate analog. Melbourne Airport is more similar to Laverton, whereas the upper station on the far left is the urban regional office. The results show that the changes between Regimes 1 and 2 are comparable with those projected for 2045–2060.

Consistent with Figures 2 and 3, recent regime changes rival changes projected for mid-century. Therefore, even with state-of-the-art downscaling techniques, climate models tend to underestimate future changes when compared with the recent regime shift.

#### 3.2.2. Eastern Australia

Clarke, et al. [13] analyzed future fire weather using FFDI calculated directly from the output of four climate models for the whole of eastern Australia. They partitioned regions according to rainfall patterns coinciding with fire regimes into summer tropical, summer seasonal, uniform and winter seasonal. These run from north (tropical) to south (winter) through eastern Australia. The resulting pattern of change is consistent with the pattern of shifts summarized here. The largest changes were projected for the winter-dominated region in the south by about 25%, reducing further north where only small changes were projected, dominated by decreases to 2050, then a return to current status by 2100 in the summer tropical region. These patterns included seasonal duration and extremes (FFDI > 40). By 2100, all three models were projecting an earlier fire season and more extremes [13]. Two of the models projected increases in humidity everywhere and the larger increases were where FFDI decreased. Decline and increase patterns occurred where temperature increases overcame humidity increases and drought factor decreased.

#### 3.2.3. Tasmania

Fox-Hughes, et al. [17] assessed future ΣFFDI for Tasmania by dynamically downscaling output from six climate models using CSIRO's Conformal Cubic Atmospheric Model. They calculated FFDI on a 10 km grid and compared these with station data, concluding that the current climatology was reproduced reasonably well. They produced projections for six regions, starting from 1961 to 2090 assuming a linear trend, calculating a low, mid, and high trend based on the model ensemble. Their baseline period was 1961–1980, for an ΣFFDI of 1206 across the six regions (not the whole of the state), whereas the base regime for HQD ΣFFDI 1957–1958 to 1998–1999 was 1403 (and 1316 for the 1961–1980 period). The mean ΣFFDI 1981–2010 from CCIA 2015 was 1395 for Hobart and 1494 for Launceston, showing that the HQD ΣFFDI is more representative of Tasmania's higher fire danger regions.

The current regime for HQD ΣFFDI for Tasmania spans 1999–2000 to 2019–2020, a 36% increase over the previous regime (1316 to 1792). Table 5 shows the relative increases from Fox-Hughes et al.'s [12] projections, extrapolated from the baseline to the current regime of 1999–2019, and to 2090 (2081–2100). The largest proportional change to the current regime is 9.7% to 14.8%, up to about one-third of the observed change. The mid to high trend to 2090 is of a similar magnitude to the estimated shift in 1999–2000 for the lower fire danger regions but the higher fire danger regions only project half the current regime change. This suggests that climate models may underestimate future changes in Tasmania more than in other regions.

**Table 5.** Calculations of relative change in ΣFFDI from data in Fox-Hughes, et al. [17], showing the range of change from the baseline of 1961–1980 to the current regime of 1999–2019 and the trend amount reached in 2090.

| | Western | North-East | Central Plateau | East Coast | Upper Derwent | Midlands |
|---|---|---|---|---|---|---|
| Baseline (1961–80) | 345 | 932 | 883 | 1521 | 1741 | 1817 |
| 1961–80 to 1999–2019 | | | | | | |
| Low | 9.7% | 4.3% | 8.6% | 3.2% | 3.6% | 4.4% |
| Mid | 12.1% | 5.9% | 10.6% | 4.6% | 5.1% | 5.8% |
| High | 14.8% | 7.4% | 12.8% | 6.0% | 6.6% | 7.3% |
| 1961–80 to 2081–2100 | | | | | | |
| Low | 30% | 13% | 26% | 10% | 11% | 14% |
| Mid | 37% | 18% | 33% | 14% | 16% | 18% |
| High | 45% | 23% | 39% | 18% | 20% | 22% |

Fox-Hughes, et al. [17] also calculated the 99th percentile of FFDI, which is closest to the HQD Days Hi+ category for the east of Tasmania [42]. Days Hi+ registered a shift in 1997–1998 from 15 to 25 days per year. Although an estimate for the whole of Tasmania, this average is close to changes for the higher-risk regions. Estimated increases in the 99th percentile over the course of the 21st century were up to 5 days per year [17]. The largest observed changes and those modeled were in spring, spreading into summer over time [17], showing a large difference between observations and projections.

Events at the more severe end of the scale were investigated by Grose, et al. [43] using dynamical downscaling. These events extended into Days Sev+. They found that downscaling reproduced events better than the coarser climate models but led to less change than in the host models. Extreme fire weather averaged 0.7 to 0.8 days per year in the baseline and 0.6 to 1.1 days per year toward the end of the century. Based on the relative change for ΣFFDI to the current regime of 28% and even more for days Hi+ and VHi+, this seems quite low.

3.2.4. New South Wales

Clarke and Evans [14] conducted a high-resolution study based on Clarke, et al. [16] but downscaled further onto a 10 km grid. Their baseline was model years 1990–2009 and the change period 2060–2079. The state average change was −162 to 842 in ΣFFDI. We lack a direct comparison but from their baseline, the current regime 2002–2019 represents an increase of 193, 23% of the upper limit of 842. For days Sev+, the range given was −1.7 to 4.5. The current regime represents an increase of 0.8, 18% of the upper limit. If the shifts from Regime 1 to 2 are attributed to external forcing, then the lower part of the projected range (−162 to 193) can be retired, and the upper part of the range can be considered more likely to occur.

3.2.5. National

Clarke, et al. [16] investigated changes in fire weather and fuel load using the NSW and ACT regional climate modeling project that downscales GCMs into a set of regional climate models, selecting those that performed best [44]. They compared model years 1990–2008 and 2060–2078 for temperate (57–550 ΣFFDI), grassland (−186–1372 ΣFFDI) and subtropical regions (−186–1372 ΣFFDI). If we take SE Australia as representative of the temperate area, then the change of the current regime from the baseline is +217 or 39% of the worst case by 2069, reinforcing the previous point.

Dowdy [35] presented a methodology for seamless predictions and projections of fire weather for Australia. The idea is to use multiple data sets and models in delivering a seamless service that can inform tactical responses on a daily or even real-time basis through strategic long-term planning. This data set builds on a daily climatology of FFDI from 1950 that has been under construction for the past few years [45,46]. It uses temperature, rainfall, and vapor pressure from the Australian Water Availability Project (AWAP) [47] and recalibrated wind speed from reanalysis data. It is spatially detailed, with a 0.05° grid spacing.

Real-time fire weather forecasts can be run with the Bureau's ACCESS model, initialized seasonal forecasts with the same model, and long-term projections using an ensemble of GCMs to sample intermodel differences [35]. Model output was scaled to observations using a quantile matching to extremes method that scales between ranked data across two probability distribution functions while allowing for changes in the distribution and extremes. The training period was 1975–2017 and followed three steps: (a) calculate probability distribution functions (pdfs) for each grid cell, (b) match pdf ranks, (c) calculate the five highest and lowest model values with the mean difference with observation used for bias corrections [35]. The input values for FFDI were used and the operation was carried out separately for each season. The correspondence for the 95th and 99th percentiles 1990–2009 in map form is close, especially for the former.

Projections of daily FFDI to 2100 were calculated for 15 GCMs forced by RCP8.5, adjusted using the quantile method [48]. For the last 40 years of the run, a running mean anomaly was removed from the data for quantile matching and then returned. This provided a better representation of changes in the pdf in response to greater forcing [35].

Quarterly results were presented in map form for 2060–2079 and for 2020–2039 [35]. This method of presentation does not allow for direct comparison with the regime changes in FFDI reported here. However, Dowdy [35] estimated changes of 2–5 days per year for the 99th percentile 2060–2079 for many regions of Australia. Taking the baseline daily FFDI for four Victorian stations from 1972–1973 to 2009–2010 the increase between Regimes 1 and 2 in 1996–1997 ranges from 2.4 to 3.0 days per year.

Therefore, while these downscaling methods will reduce model bias somewhat, concerns about how the historical regime shift is factored into both baseline and projections persist.

## 4. Discussion

### *4.1. Looking Back*

The main aim of this paper has been to compare and contrast recent regime shifts in fire climates for Australia with longer-term projections of the FFDI. Earlier results showed that a regime shift in FFD indices occurred around 2000 for most parts of Australia and a decade or more later further north [1]. Here, we show the changes are similar to, or larger than the upper limits projected for 2030. For Days Sev+ (FFDI > 50), they rival median limits toward the end of this century. The exceptions are South Australia and Western Australia, which both have a large projected upper limit. According to Dowdy [35], large increases in the continental interior are partly due to the large base rate and scaling method used.

This suggests that for the past two decades, much of Australia has been experiencing fire climates anticipated for the period 2015–2045. Population-weighted, this is most of the country. Ironically, when the CCIA2015 projections were being compiled (2014–2015), the climate had been at those levels for over a decade in southern states and regions.

In addressing these disparities, four factors need to be considered:

1. How the response of fire climates to radiative forcing, and climate more generally, is conceptualized;
2. The capacity of climate models to accurately represent those responses;
3. How projections of future change are constructed; and
4. How those projections translate into an understanding of changing risk.

1. Climate change is invariably considered a trend. Trend is often used as a synonym for change in the literature, implying that is the only type of change possible due to forcing. When there is no potential for an alternative explanation, nonlinear change can only be an exception, never the rule. Many studies have acknowledged the nonlinearity within the FFDI record [12,19,21,39,46,49–51], but still considered the forced component to be trend-like.

Some of these studies analyzed the two periods around the regime shift separately but did not feel justified in suggesting the nonlinear changes were due to anything other than internally generated variability. Note that efforts to comprehensively assess the influence of different modes of variability in FFDI, such as Harris and Lucas [21], have found their footprint in interannual variability but not longer-term change.

Only Jones, et al. [29] explicitly attributed regime change in FFDI in Victoria to a forced response, having previously shown that shifts in Tmax and Tmin in SE Australia were both externally forced [31]. Later analysis showed that the shift component of global mean temperature had 2.9 times the explanatory power of the trend component in explaining climate sensitivity for 94 climate models [34]. This work concluded that regional and global nonlinear changes were both part of the same response mechanism [34].

2. Climate models are clearly underestimating changes in FFDI. RH and TmaxFS were identified as the main contributing factors in [1], both occurring as regime shifts. The primary driver was the rapid decrease in RH, with the resulting land-surface feedback influencing the timing and size of fire season Tmax.

In a related paper, we showed that climate models driven by historical forcing to 2005 and RCP4.5 from 2006 produce regime changes in RH (32 models, 170 shifts, 19 decreasing and 13 increasing), but significantly underestimated current and future change. Global mean RH from the HadISDH data set [52,53] shifted by $-0.27$ points in December 2001 and $-0.29$ in November 2011, totaling $-0.56$ points [2]. Other authors have addressed these changes as trends [3,4]. No model of the 32 tested reproduced these decreases and only four of the records met or exceeded the observed changes by 2100, the first in 2054 [2]. The models' inability to reproduce these changes is the major contributor to their underestimation of change in FFDI.

3. By comparing the different projections of future FFDI for Australia with observed fire regime changes, we can see how projections have evolved since 2005. Methods of construction changed little between the earliest release [11] and the later issues in 2015–16 [15,18] even though the number of available climate models climate increased and spatial resolution improved.

In these studies, projections were constructed as time-slice experiments for given future dates. Baselines were statistical, of sufficient length to represent a mean climate, and were periodically updated. The change measured between the model baseline and the future period was added to the observed baseline. FFDI was originally calculated from data derived from the nearest GCM grid points, but increasingly, these inputs are being downscaled dynamically, using regional climate models, statistically, or both.

Over the past five years or so, the amount of data being made available for assessment has increased substantially. It is being driven by the need to better understand current and future fire risk at local scales. Both adaptation to climate change and disaster management are conducted at the state scale, while the forecasting and climate modeling programs aiming to predict fire risk are being conducted at the national scale. The need to integrate these is well recognized, but until recently, the lack of coordinated funding arrangements has limited agencies to making do with what is available.

Dynamical downscaling is being widely pursued and includes Climate Futures for Tasmania [43,54,55], NARCliM covering New South Wales, the Australian Capital Territory and South Australia [44], Queensland Future Climate [56], and Victoria's Climate Projections 2019 [57] and is being planned for Western Australia. Most either provide FFDI or the inputs for FFDI.

Methods for projecting change are becoming more sophisticated. Transient runs allow the construction of change pathways and storylines, providing the capacity to combine quantitative and narrative approaches. However, if trend analysis is combined with the systemic underestimation of future change, future risks will continue to be underestimated.

This limitation has also affected attribution studies. Measuring the forced component of FFDI as a trend, either from observations, or climate model output tends to have a similar effect. Analyzing the input variables to FFDI, Dowdy [46] was able to directly attribute changes in extreme temperature while noting that all input variables to FFDI followed consistent trends for spring in southern Australia. Even though he acknowledged the significant nonlinearity in the latter part of the record, it was concluded that the attribution of change was only partial [58]. Van Oldenborgh, et al. [59] compared trends in the maximum 7-day annual event in the Fire Weather Index calculated using reanalysis data from 1979 to 2019–2020, finding large trends. Their Figure 3a illustrating this index [59] shows clear regime-like behavior. When they compared the reanalysis with the mean outputs of 11 climate model ensembles, the models showed positive trends that were considerably weaker than the reanalysis results [59].

The historical effect of how linear trend analysis underestimates regime change is shown in Figure 4. HQD Days Sev+ for SE Australia are shown with trends beginning in 1957 and ending in five-year intervals from 1996 to 2021. The first two are horizontal, and the trend ending in 2006 captures about half the change of Regime 2. This stays roughly constant for the following periods, not quite reaching the level of Regime 2 by 2021. The 2030 (2015–2045) projected change is situated just above Regime 2.

This shift occurred when global mean temperature moved from about 0.5 °C to 0.8 °C above pre-industrial levels. For perspective, the minimum projected Australian average increase in Tmax above the 1981–2010 baseline for 2030 from CCIA2015 was 0.9 °C and for 2090 was 1.8 °C. The median warming in Tmax projected for 2090 was 2.8 °C, whereas Table 3 shows Regime 2 to be two-thirds or greater of the median ΣFFDI in 2090 for most states and roughly equal for Days Sev+ for the eastern states. This suggests the models are less sensitive than observations by a factor of three to four.

4. A fire climate regime is defined as the incoming climate external to a region that influences the propensity for wildfire to occur. It represents a physical climatic state, whereas a reference period or baseline defined by a period of convenience (e.g., 1981–2010) is a statistically defined state. State changes in FFDI are physically driven by regime shifts RH and Tmax, amplified by changes in drought factor (or soil moisture more generally), with their interannual variability also influenced by rainfall patterns [1].

A fire climate regime differs from a fire regime, which describes when, where, and what kinds of fires affect a particular place [60,61]. Bradstock [62] described four measures that can be used to define a specific fire regime: biomass production, biomass readiness to burn, fire weather, and ignition sources. They also exist on different scales. For example, different fire regimes can exist and occur closely together (e.g., grassland, dry sclerophyll forest) but are subject to the same prevailing conditions.

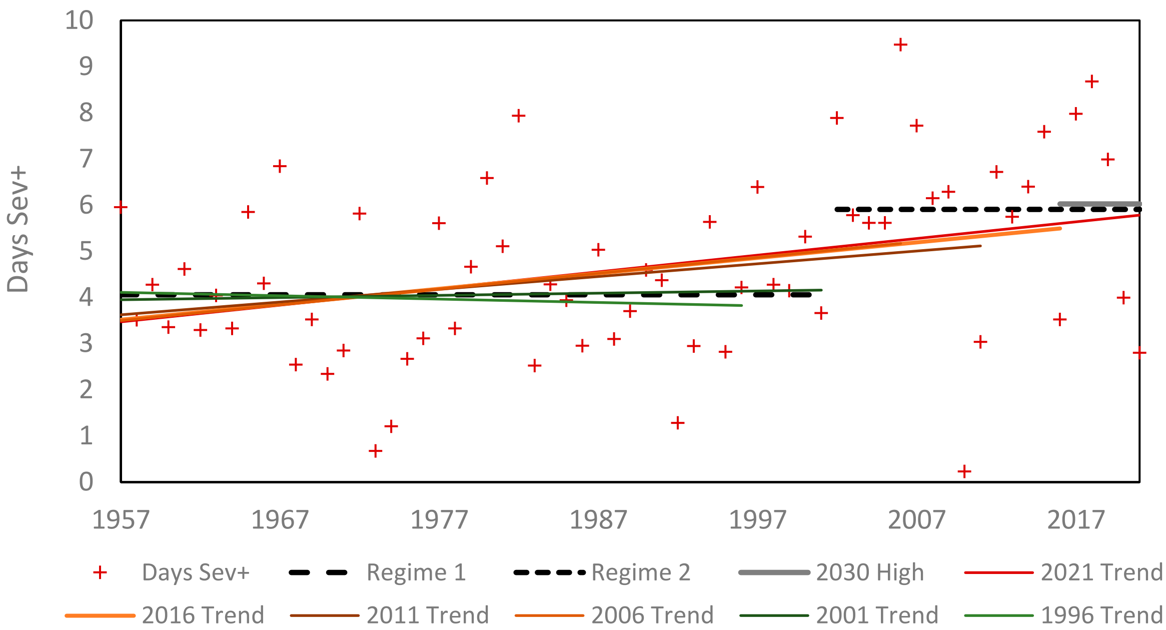



**Figure 4.** Modeled annual Days Sev+ from 1957–2021 for SE Australia shown with Regime 1 and 2 means for 1957–2001 and 2002–2021 overlain by linear trends starting in 1957 and ending in five-year intervals from 1996 to 2021. Also shown is the projected 2030 high limit from CCIA2015.

A comprehensive assessment of fire risk at a given location requires understanding how all four may change. This needs both a climate model and fire simulation model at the very least, and a fully coupled high-resolution climate-biosphere model at best. Modeling individual fire behavior involves local feedback which adds significant uncertainty to future projections. A fire climate regime addresses patterns of externally driven fire weather and needs to be correctly defined in order to progress the other three measures: biomass production, readiness to burn, and natural ignition sources.

In a comparison with the 2019/20 NSW fires, Sanderson and Fisher [63] assessed four current earth system models in the CMIP6 archive that had combined climate, vegetation growth, and fuel conditions to simulate wildfire. The scale of the recent fires was unmatched in simulations of current or future conditions, for NSW, Victoria, Queensland, or Australia as a whole [63]. According to Sanderson and Fisher [63], the models have to get a lot of processes right before they can estimate future fires well enough to contribute to management. This accentuates the need to have simple and robust tools for planning now, given that the regime shifts documented here have been in place for almost two decades but are not being explicitly acknowledged as such.

The ability to analyze the external and internal drivers of fire risk separately is especially important for addressing climate policy, land-use policy, and risk mitigation. The main aim in characterizing wildfire risk is not to predict fires in fine detail over the coming decades but to assess externally and internally generated risks independently, and then test various interventions to mitigate those risks. Fine temporal and spatial details are needed, but the methods used will be strongly diagnostic rather than predictive.

The systemic underestimation of changing FFDI using current methods and tools is a significant barrier to achieving this. Incorporating information on steady-state fire regimes and regime shifts into the observation, modeling, and projection of fire danger indices is urgently needed.

### 4.2. Looking Forward

As described by Dowdy [35], the shared aim of Australian agencies involved in emergency management is to develop the capacity to provide and utilize seamless advice on fire weather on a range of timescales from hours to many decades. This contributes to a larger program in Australia [64] and is a key focus of the World Meteorological Organization (WMO) and World Climate Research Programme (WCRP), which the Australian efforts draw from.

Seamless projections and predictions involve the development of climate models capable of operating over those timescales; associated climatologies that be used to link past present and future; and a common set of methods, tools, and practices to deliver and interpret climate information. While this information is tailored for multiple uses, its scientific form and content are dictated by current theory and practice. In practice, this involves the application of the signal-to-noise model to represent the response to radiative forcing.

This effort comes in two parts. The first part is a forecasting component, extending from hours to decades, and is a focus of the WMO Integrated Processing and Prediction System. The second involves constructing projections of future change. Both are key components of the WCRP strategy 2019–2028, where the scientific objectives are to improve prediction of the near-term evolution of the climate system (forecasting) and to quantify the long-term response of the climate system (projection).

Prediction is initialized in the current weather or climate state and driven forward for the period of interest. Ensembles indicate the most likely state or sequence of events, which make up the forecast.

Projections due to external forcing, are generally assumed to be independent of initial conditions and are only considered meaningful when a linear signal emerges from the variations about a fitted trend. For variables like FFDI, which have high intrinsic variability, this takes longer than for less noisy variables such as temperature. Prediction and projection components will also overlap on decadal timescales, sometimes substantially. Model ensembles focus on the consensus trend as providing the most likely outcome for a given set of drivers. This removes the possibility of investigating regime shifts, which carry the greatest risk.

The presence of confirmed regime shifts in variables such as temperature, rainfall relative humidity and related moisture variables, and FFDI means that the biases illustrated in Figure 4 can affect the construction of existing climatologies and projections of future change. It is important to understand the implications of both.

An important part of our strategy in constructing FFDI from BoM high-quality data was to provide the best available homogenous time series on a regional basis. Thirty years of experience in analyzing regime shifts using the bivariate test shows that as the underlying data are improved; if regime shifts are present, they will become more distinct. This holds both for Australian and global data sets. Therefore, even though the HQD model may slightly underestimate FFDI and its extremes [1], it can be considered temporally consistent for each region.

Adjustments improving the quality of baseline data are best carried out spatially. Homogeneity is established using a reliable reference and then used to adjust adjacent locations where anomalies are detected. If this is performed on daily data and regime shifts become more distinct in annual data, there are clearly no artifacts in the process.

Spatial climatologies, such as those in the AWAP and the BoM FFDI data set often involve compromises when observational data are either unavailable or in a fit state to be adjusted using this method (e.g., too sparse or disjointed). This may affect the representation of regime changes in two ways. The first is where longitudinal adjustments are made from a mean or trend. The second is where data are introduced from another source. An example of the latter is windspeed from reanalysis data used in both the BoM FFDI and VicClim4 FFDI for Victoria. Best practice would involve assessing whether these applications smooth out any nonlinearities that may be present in the existing data.

Longitudinal analyses can also be problematic when used to assess return periods from either baseline or model data. Sensible practice is to use as long a record as possible, but this increases the chance that a regime shift may be present. If so, estimates of extremes, such as pyrocumulonimbus events, will be biased.

If a statistic is created from a reference period that crosses a regime shift, it will tend to overestimate a prior baseline or underestimate the current state. One strategy to counter this is to de-step the data by removing regime shifts. When nonlinear changes are present, this is superior to detrending. Whether variability has also undergone regime change also needs to be checked. In shifting from Regime 1 to Regime 2, variability almost doubled in some regions due to the presence of very low FFDI wet years combined with very dry and hot high FFDI years [1]. The hydrological cycle has become more intense with abruptly warmer conditions.

Creating climatologies that are both temporally and spatially homogenous that can accurately represent any regime shifts present is a challenge. However, the pay-off will be substantial if historical changes in risk are better represented. It will create a benchmark that can only be improved upon. Doing this can also provide advantages over the use of trends. If a shift to a new regime can be identified and attributed, then the externally driven component of fire risk can be re-evaluated immediately, rather than dealing with the signal-to-noise problem presented by short-run trends.

Even if baseline climatologies consciously incorporate regime changes, this does not fix the problem of systematic underestimation of FFDI by climate models.

Ongoing programs predicting seasonal fire danger will not have this problem, because they are initialized in Regime 2. The history of the Victorian Country Fire Authority's days of declared total fire bans provides an example. Correlation of the annual total fire ban days with HQD Days Hi+ from 1957, showed a shift from 0.26 to 0.81 after 1977–1978 ($p = 0.002$). A search could not locate evidence of a change in forecasting methods but one must have occurred to produce this outcome.

The subsequent move from total state bans to district bans from 1986–1987 has not affected the results. Total fire ban declarations since 1978–1979 shifted in 1996–1997 from 8.0 to 13.6 days per fire year at $p < 0.05$, an increase of 70%. A running correlation of 21 years since 1978 shows that the relationship between HQD-derived FFDI and declared days of total fire ban remains around 0.8. This is consistent with total fire ban days being declared in the mid-range of state-wide FFDI of 25–49 and shows that declared total fire ban days in Victoria have followed the regime shift.

This example demonstrates that sufficiently accurate forecast methods following the evolution of climate will reproduce and regime shift in the record, even if it is not formally recognized. However, projections of future fire danger will continue to be compromised if regime change is not factored in. This is clearly a barrier to seamless prediction–projection processes and needs to be overcome.

Quantile scaling of the type described by Dowdy [35] can be adjusted to allow for regime changes but will not fully overcome the inability of models to adequately represent changes in atmospheric moisture. A first step would be to analyze climate model output for regime shifts in FFDI, something we have not yet done. It may be possible to adjust for the difference in sensitivity between observations and models but this would have to be explored.

If global climate models systematically underestimate future fire risk, improvements such as finer resolution and more detailed simulations of land-surface–atmosphere interactions in regional climate models may not achieve the desired results. The global models also underestimate other variables on the hydroclimate-pyroclimate spectrum, such as extreme rainfall. The solution is likely to come from improving models' large-scale thermodynamic response to forcing rather than the small-scale processes addressed by downscaling.

Most of Australia has experienced regime changes in pyroclimate, causing abrupt changes in fire risk that to date have not yet been fully recognized. Benchmarking these changes provides a better understanding of where we are situated with respect to past and present baselines and potential future change. This would be a first step toward integrating climate regimes into future projections. If more regime changes in fire climates are to be experienced in the future, they need to be planned for.

### 4.3. Conclusions

A fire climate regime is a measure of the external climatic influence on fire danger. For Australia, we have shown that these regimes occupy steady states and can shift abruptly as the climate changes [1]. Regime shifts occurred around the year 2000 in the eastern and southern regions of Australia, and about a decade later further north in tropical regions [1].

This paper compares this new regime with low and high projections of future fire danger centered on 2030 and 2090, measured as units of total annual FFDI and days per year of severe to catastrophic fire weather. For much of Australia, the current regime is close to, or exceeding the high projections for 2030. The two exceptions are states with large, arid interiors, namely South Australia and Western Australia. This abrupt change in fire danger preceded projected changes derived from climate models by up to three decades. Similar changes could happen in the future.

The two major reasons for these underestimates are the (1) systematic underestimation of reductions in available atmospheric moisture by climate models (measured as RH) and (2) the routine treatment of climate change processes as trends when they could be more accurately represented as shifts in steady-state regimes. We discuss how these shortcomings may be addressed in order to produce seamless predictions and projections of future fire risk. Finally, given the global nature of changes in fire season length [1,65] and moisture reductions [2,4], these underestimates are global in scope and will need to be addressed more widely than just for Australia.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire7040113/s1, data and results in the file JR2024SuppMat.xlsx.

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