Towards linking climate and weather phenomena to road safety outcomes part 2 of 3: Longer-term influences of climate drivers

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Key Findings

- The cyclic nature Southern Annular Mode has an association with the cyclic nature of fatal crashes.
- The centroid of annual fatal crashes moves consistent with weather patterns.
- The variability of annual road deaths is associated with long-term climate.
- The 24-hour distribution of casualty crashes varies in response to weather movement.
- The large difference in fatal crashes in 2019 compared with 2018 can be related to weather.

Abstract

This paper is Part 2 of a three-part series illustrating how climate phenomena and weather metrics vary within a year and between years that can effect road safety. Part 1 identified the breadth of weather factors collectively contributing to crash risk and consolidated relevant research. The key climate drivers for Victoria produce complex interactions forming short-term and long-term weather patterns influencing crash occurrence and their spatial and temporal distribution across the state. The study found that the Southern Annular Mode (SAM) with its roughly 14-day cycle has the most significant influence on Victorian casualty crashes (also cyclic). A Chi-Square Goodness-of-Fit Test showed a statistically significant association (at the 0.05 significance level) between casualty crash numbers and each of the climate drivers. For fatal crashes, however, there was no statistically significant association, likely due to low numbers and randomness. Whilst this paper focuses on Victoria, other jurisdictions can use the approach presented using their local context of climate, latitude, and geography to identify patterns and influences on crashes. Understanding climate influences on crash occurrence within and between years assists strategy development for improving road safety and reaching the target of zero deaths.

Keywords

climate, weather patterns, cycles, crash risk, spatial, temporal

Introduction

This paper, the second paper in a three-part series, examines variations in Victorian weather patterns over a decade, linking them to variations in annual fatal crashes to provide a more holistic understanding of crash risk as explanations are often inadequate for rises and falls in annual road deaths. The paper seeks to highlight additional associations with crash risk from meteorology that has received minimal attention in Australia.

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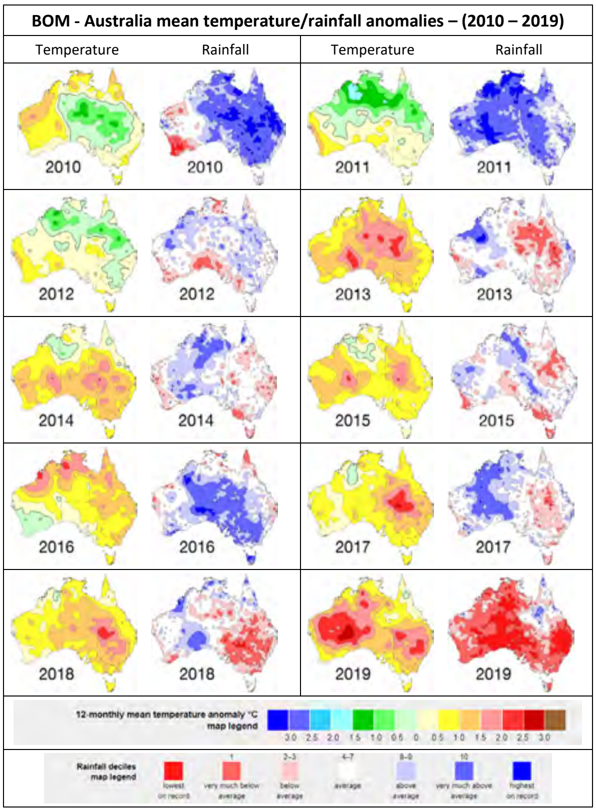


Figure 1. Australia annual mean temperature/rainfall anomalies, 2010-2019 (compiled from BOM, n.d.)

Many key meteorological records published by the Bureau of Meteorology (BOM) were reviewed, including temperature, precipitation, and annual climate summaries. Some years are appreciably hotter or colder, and/or wetter or drier than others. Yearly, monthly, and daily variations exist across different parts of Australia or within a state (see Figure 1). When correlated at the granular level (spatially, temporally, with travel demand patterns), new understandings of crash risk emerge.

Whilst this paper focuses on Victoria, there are many parallels for other jurisdictions. Jurisdictions will need to firstly understand their local context of climate, latitude, and geography. The variations in climate and weather patterns are noticeable across capital cities and areas with high population densities and road use demand and can help explain the annual and temporal variations seen in fatal crashes in and within jurisdictions.

The paper examines the cyclic nature of three climate drivers influencing Victoria's long-term climate and short-term weather patterns and the cyclic nature of fatal crashes. It examines the relationship between absolute movements (variability in weather over the year) in the Southern Annual Mode (SAM) and annual fatal crashes. SAM has the greatest influence on Victoria's daily weather, having a cycle of approximately 14 days. Southern Victoria, especially Melbourne, is known for having four seasons in one day, substantially due to SAM's variability in relation to Victoria's latitude and geography. This paper looks at time-shifts over the day of fatal crashes between colder and hotter years, and between drier and wetter years, and variations in fatal crashes for the decade (2010-2019).

Widespread concern arose in Victoria as a result of the apparent rise in fatal crashes in 2019 (248) following a record low in 2018 (202 crashes, 213 fatalities). In 2018 fatal crashes were 20% below the 2008-2017, 10-year average (252), whereas in 2019, the number of fatal crashes (248 crashes, 266 fatalities) was close to the 10-year average. Climate received extensive media attention during 2019 with extreme hot weather, melting pavements and major bushfires. The limited explanation for the increase in fatal crashes prompted detailed examination of differences in climate and weather between 2018 and 2019.

Methods

The crash data were sourced from the Department of Transport Road Crash Information System (RCIS). Weather and Climate data were sourced from the BOM website. Microsoft Excel, QGIS and Microsoft Power BI were used for the analysis.

Yearly and monthly crash trends (fatal and casualty, although the latter presented limitations due to data discontinuities and incompleteness) were investigated from 2010 to 2019. Analysis identified large variations between the same month in different years suggesting underlying causes, leading to an investigation of climate and weather metrics. BOM annual and monthly summaries were analysed for the same period as the crash data. Hourly distribution of crashes were investigated and were markedly different, suggesting weather as a possible influence. The cumulative distribution of crashes, both by day of year and by hour of day was plotted.

Yearly patterns were investigated in terms of crash location, crash centroids and variations in weather metrics, including maximum temperature, minimum temperature, rainfall, solar radiation, and water vapour pressure. Analysis considered monthly and daily data to identify the variability of measures and their resulting weather manifestations. To examine the movements in crash centroids, averages of the spatial coordinates (250 fatal crashes per annum) were calculated and plotted for total Victoria, country and metro.

Preliminary statistical analysis of the relationships between climate drivers and crashes (casualty and fatal) was undertaken, including a Chi-Square Goodness-of-Fit Test. To further investigate the relationship between weather variability and fatal crash numbers, absolute SAM movements (sum of daily movements) were calculated (by difference between consecutive day measurements) and summed for the entire year. For example, a SAM value of 0.5 on one day and a SAM value of -0.3 on the next day results in an absolute movement of 0.8 units. The annual average daily movement of SAM, its mean, and standard deviation, and the yearly total absolute movement were plotted against the fatal crash numbers. Daily values were plotted against daily fatal crash numbers using rolling averages (14-day) to identify underlying trends and cyclic patterns.

A month-by-month comparison of weather and climate between 2018 and 2019 was undertaken, as well as detailed analysis for the first six-months (where 96% of the 48 additional fatal crashes occurred) and the second six-months (which were similar in both years). February, April, May, and June had the largest increases so in-depth analysis was undertaken on these months for both 2018 and 2019, including investigation of weather and crashes on a daily and hourly basis to identify differences. Analysis for April is included in this paper.

There are limitations to these analyses as they do not specifically take account of other factors, such as pavement friction levels and traffic volumes (demands). These other factors influence crashes but are themselves impacted by climate and weather and therefore are areas recommended for further research. In many cases, it is not daily traffic volumes, but rather traffic density, exacerbated by weather, that impacts crashes (Hovenden, Zurlinden, & Gaffney, 2020). Another area for further research is undertaking statistical modelling of crash and weather data with involvement of meteorologists.

Results and Discussion

Long-Term Annual Variations in Climate, Weather and Fatal Crashes

Figure 2 shows yearly variation in Victorian weather, revealing marked differences in maximum and minimum temperature, rainfall, with considerable geographical variation. Monthly and daily maps show larger variations in weather (see Figures C1 to C3 in Appendix C for April 2018 and 2019).

Figure 2 shows 2014, 2018 and 2019 are the three hottest years, 2010, 2011 and 2012 are the three coldest years, 2010, 2011 and 2016 are the three wettest years and 2015, 2018 and 2019 are the three driest years. These maps show different locations in Victoria are affected differently each year with respect to meteorological metrics which needs to be considered in crash analysis.

Variations in Annual Centroids of Fatal Crashes

Figure 3 shows the centroids of fatal crashes in total Victoria, country Victoria and metropolitan Melbourne, for each year (2009-2019). The year 2009 was included as it had the lowest annual solar radiation in recent years, indicative of less sunshine (potentially colder days), and lower visibility (due to presence of clouds). In contrast, 2019 had the highest annual solar radiation (see Figure 4), indicative of increased sunshine (more sun-glare) and hotter weather.

Considerable variation in average eastings and northings of fatal crash centroids is seen each year. The movement in eastings was 35 kms and northings was 14 kms, a total distance of 38 kms (corresponding to the coldest year and hottest year). This is substantial given nearly half of the fatal crashes over this period occur in a concentrated area (approximately 4% of Victoria) in metropolitan Melbourne. A wider spread is observed in the centroids of fatal crashes in country Victoria, with a difference of 62 kms in eastings and 24 kms in northings, a total distance of 67 kms. In 2019, the crash centroid was near Taradale whilst in 2009, the crash centroid was east of the Hume, near Clonbinane. Weather can likely explain fluctuations in annual fatal crashes between metropolitan and rural areas.

Variations in centroids are potentially associated with solar radiation, influenced by extent of cloud cover and moisture held in the atmosphere, including water evaporation. In the hottest year, crash centroids skewed northwest (dry, semi-desert areas) whilst in the coldest year they were skewed southeast (mountainous, damp areas). Solar radiation levels affect driver comfort (humidity), visibility (moisture and particles held in the air) and pavement friction levels (moisture held in the air or in or near the ground where it contacts the road surface). Radiation levels generally decrease with increasing latitude (colder in the south, warmer in the north), varying in intensity with season. Radiation levels continually vary with movement of climate and weather, making each day/month/year different and affecting each location across Victoria differently.

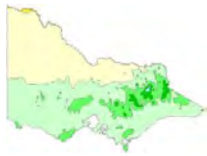
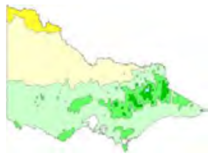
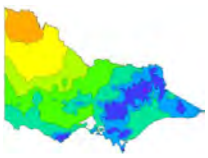
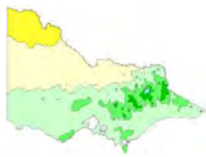
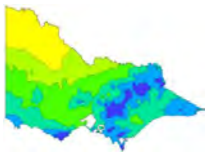
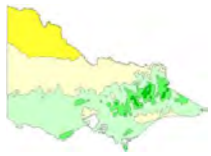
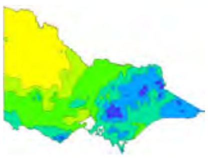
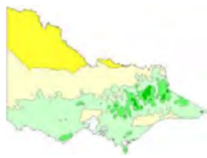
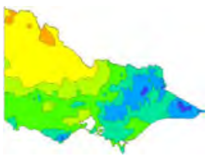
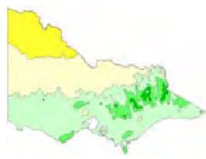
Other factors influence crash location (see Parts 1 & 3), potentially related to solar radiation levels, including pavement friction levels and duration of crash risk after rain/dew events, such as wind speed (slow moving/still air or windy conditions) combined with higher/lower water vapour pressure (humid versus dry air conditions). These factors determine whether road surfaces dry rapidly or remain damp for long periods (hours or days), elevating crash risk. Wind anomalies and cloud cover extents should also be investigated as these vary markedly between years and locations.

Cyclic Nature of Climate Drivers Influencing Weather

Re-capping Part 1 of this series of papers, three primary climate drivers affect climate and weather in Victoria:

1. Southern Oscillation Index (SOI);
2. Indian Ocean Dipole (IOD);
3. Southern Annular Mode (SAM).

Figures 5 to 7 show the cyclic nature of these climate drivers, which combine in different ways to influence the annual, monthly, daily, and hourly weather outcomes. Time lines are not the same due to data availability. Resultant weather outcomes can be weak, neutral, strong, enduring (days, months, or years, e.g., drought) or short-lived (minutes, e.g., thunderstorms and wind gusts) depending on the strength and combination of each driver.

Year and Summary of BOM Commentry	Annual Rainfall	Annual Minimum Temperature	Annual Maximum Temperature
2010 **Fifth wettest year on record** **287 fatalities from 259 crashes** Wettest year since 1974, warmer than average nights state-wide. Daytime temperatures close to average due to cool spring.			
2011 **Hot nights and plenty of rain** **287 fatalities from 259 crashes** 3rd warmest average night-time temperatures in 102 years. 12th wettest year in 112 years. 22nd warmest average daytime temperatures in 102 years.			
2012 **Warmer in parts, mixed rainfall.** **282 fatalities from 261 crashes** Above-average rainfall in the east, below average in the west and close to normal in the centre. Warmer than normal daytimes in the west, warmer than normal night-times in the south.			
2013 **Warm year with near average rain** **243 fatalities from 225 crashes** Near average rainfall for the State as a whole.Some coastal parts reported above average rainfall whilst much of the northeast was more than 100 mm drier than normal. Winter delivered above average rainfall to most parts tending to very much above average in the south, while spring saw above average rainfall in southern coastal areas but below average rainfall in the north.			
2014 **Warm year lower rainfall over much of the State** **248 fatalities from 223 crashes** Victoria's warmest year on record for maximum temperatures, second-warmest for mean temperatures and third-warmest for minimum temperatures. Rainfall was below average in most areas apart from the far east, and well below average in the central west.			
2015 **Above average temperature, below average rainfall** **252 fatalities from 231 crashes** For most of Victoria, rainfall was below or very much below average; above average rainfall was recorded mostly in the far east of the State. Maximum temperatures were above the long-term mean across the State; minimum temperatures were generally above average, with nights tending closer to average in part of the State's west.			

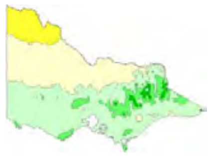
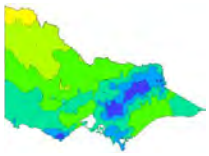
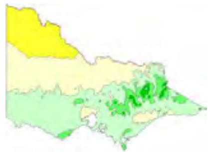
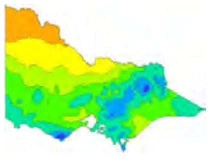
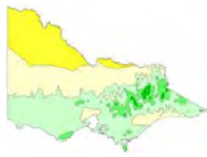
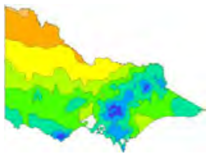
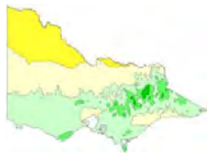
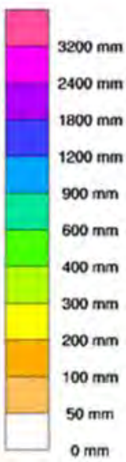
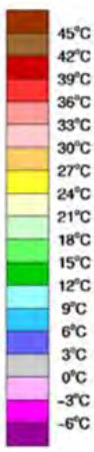
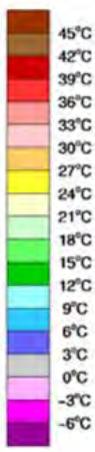
Year and Summary of BOM Commentry	Annual Rainfall	Annual Minimum Temperature	Annual Maximum Temperature
2016 **Very wet year** **290 fatalities from 275 crashes** Fifth-warmest year on record and warmest mean minimum temperatures on record. After a generally dry start, Victorian rainfall was above average, with 2016 the State's wettest year since 2011.			
2017 **Weather closer to Normal** **259 fatalities from 240 crashes (near 7-year mean)** Victorian rainfall in 2017 was slightly below average overall. Most months were drier than average, but April and December were wetter than average. 2017 was Victoria's sixth-warmest year on record, with both mean maximum and minimum temperatures above average in all districts.			
2018 **Very dry year** **213 fatalities fron 202 crashes (low no.)** Victorian rainfall in 2018 was below average, with all months except December being drier than average. Both mean maximum and minimum temperatures were above average overall.			
2019 **Very dry year tending to normal in populated areas** **266 atalities fron 248 crashes (near decade mean)** Rainfall in 2019 was below average, with most months drier than average. Rainfall totals were much below average in large parts of the State's north and east, and lowest on record in the far northwest. Days were warmer than average across all areas of the State, while nights were warmer than average in much of the State's south and east. Rainfall in Greater Melbourne during 2019 was generally below average; most months were drier than average, but May, June and August were wetter than average. Both maximum and minimum temperatures were warmer than average throughout Greater Melbourne.			
Legend			

Figure 2. Comparison of annual rainfall, minimum temperature and maximum temperature, BOM Summary, fatal crash numbers, fatalities, 2010 to 2019 (compiled from BOM, n.d.)

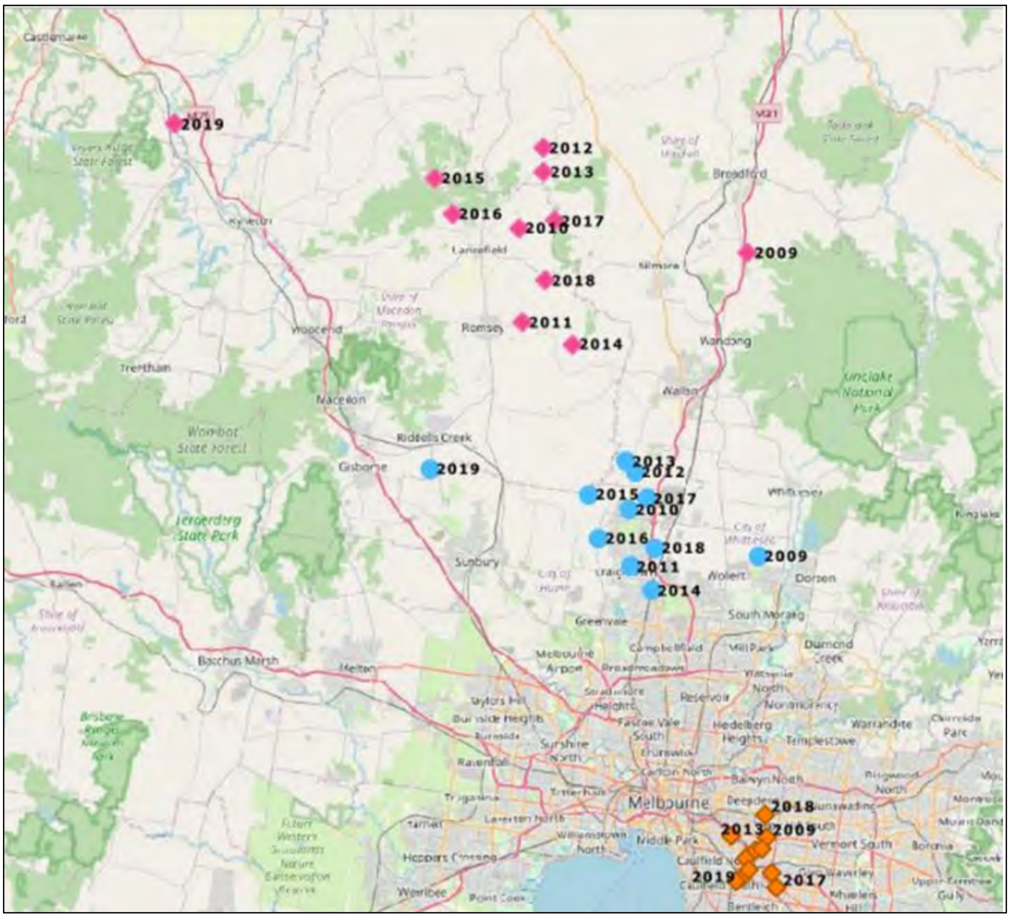


Figure 3. The centroids of fatal crashes in Victoria (blue dots), country (pink diamonds) and metro (orange diamonds) by Year, 2009-2019

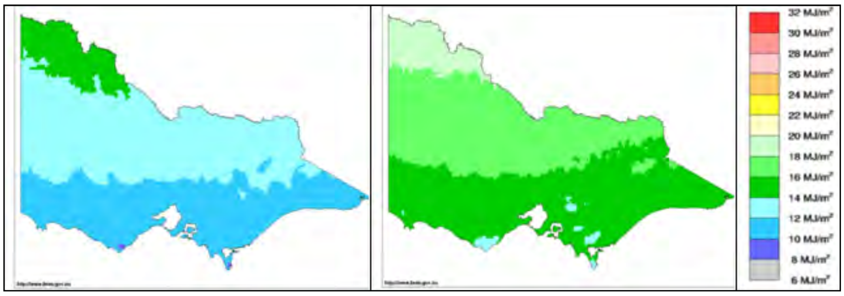


Figure 4. Solar Radiation Maps 2009 (left) compared to 2019 (right) for Victoria (compiled from BOM, n.d.)

SOI, IOD and SAM have three phases (negative, positive, and neutral) which have different effects on climate and weather depending on which phase they are in (see Appendix A). Each climate driver has different cycle times. SOI typically comprises a four-year cycle to move between the three phases, IOD a three- to five-year cycle and SAM a 14-day cycle.

Cyclic Nature of Crashes

Figure 8 shows variations in the 365-day rolling total fatal and casualty crashes. It shows that peaks and troughs do not align with calendar years, and in fatal crashes some increases or decreases span several months or several years. These long-term movements have not been adequately explained by other metrics such as road demand, road safety campaigns or treatments. Climate can offer a plausible explanation for annual variations seen at state and national levels.

When considering individual days over a 10-year period, fatal and casualty crash numbers have a cyclical pattern. Seven-day rolling averages of daily fatal crashes and casualty crashes show 25 to 30 peaks or troughs each year (see Figures 9 and 10, orange line). Rolling 14-day daily averages show similar cycles (blue line). These cycles occur on a continuum, not aligning with years, months, seasons. The smaller peaks and troughs can combine into

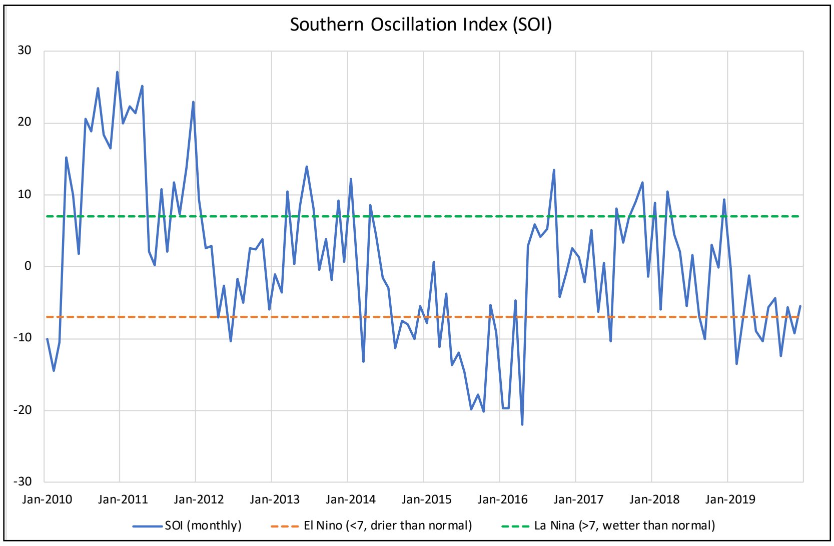


Figure 5. Southern Oscillation Index (monthly variations), January 2010 to December 2019

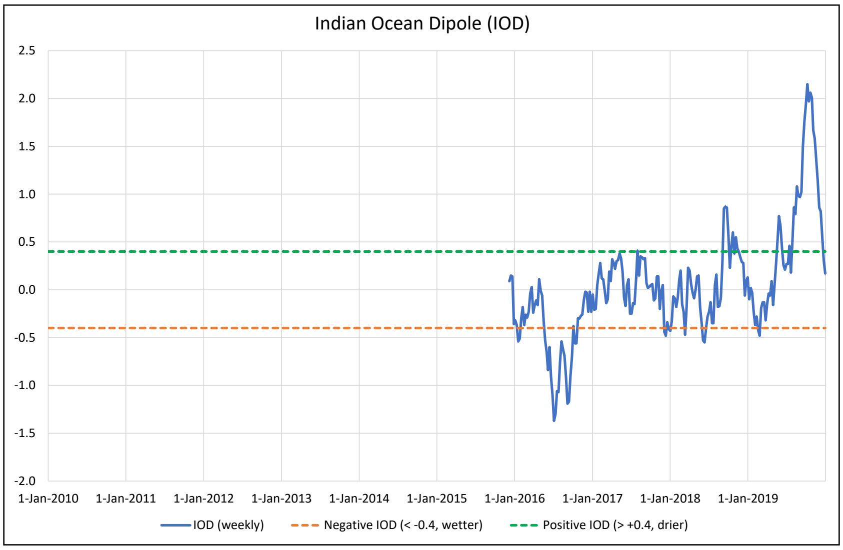


Figure 6. Indian Ocean Dipole (weekly variations), 7 December 2015 to 31 December 2019

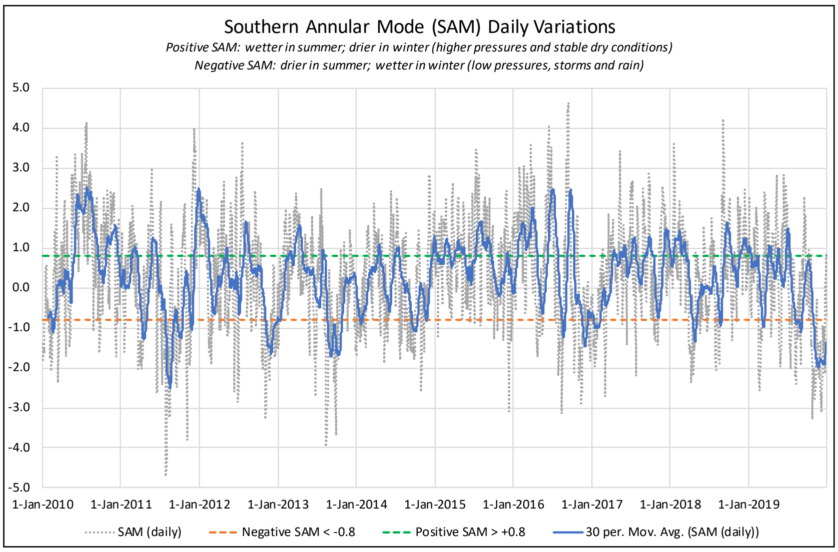


Figure 7. Southern Annular Mode daily variations, 1 January 2010 to 31 December 2019

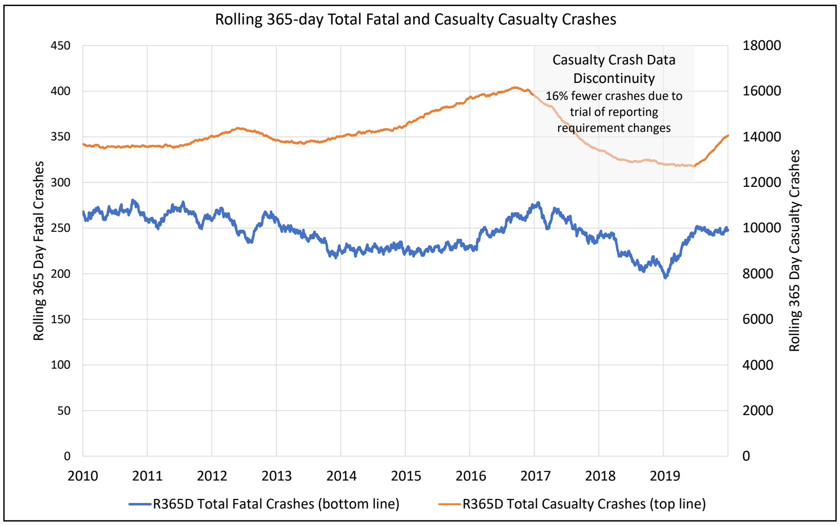


Figure 8. 10-year 365-day rolling total fatal and casualty crashes, 2010 to 2019

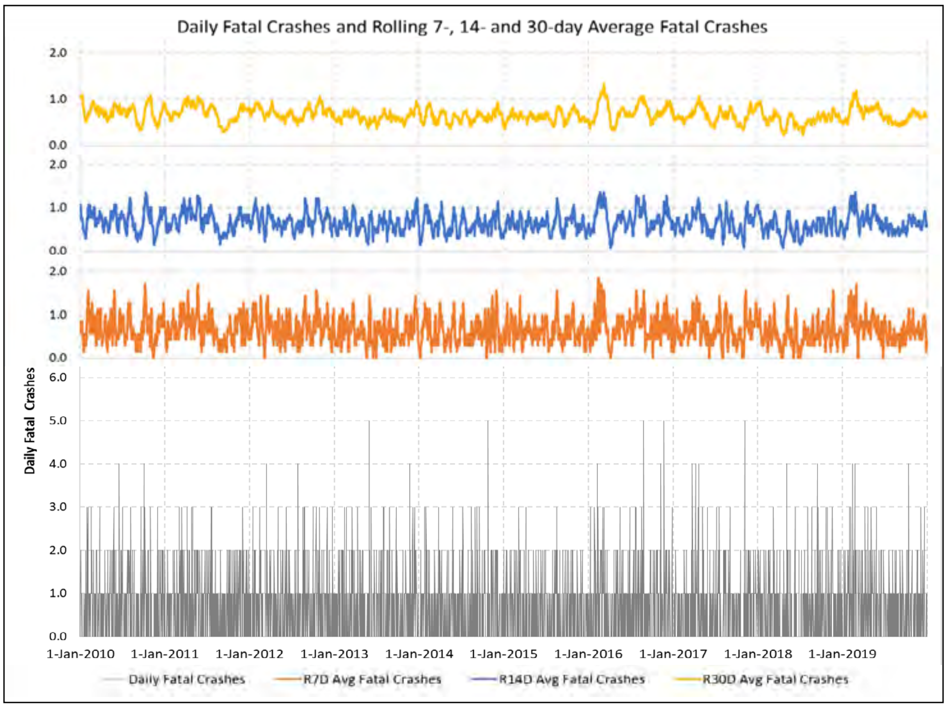


Figure 9. 10-year average daily fatal crashes, 2010 to 2019 including rolling 7- (bottom), 14- (middle), and 30-day (top) averages

larger long-term cycles of peaks and troughs, which may span for many months and can include multiple years. These longer-term cycles are not random and do not relate to traffic demands, holiday periods, road safety strategies and campaigns, and require further investigation and explanation, which climate/weather may provide in part.

Closer examination of average 10-year daily fatal and casualty crashes by month over the 2010-2019 period found certain months had higher crash numbers than others. Months are an artificial construct hence analysis of rolling 30-day totals showed a slightly different picture (see Appendix B). For example, February, March, and May calendar months had the highest number of fatal crashes. However, the rolling 30-day periods revealed the highest number of fatal crashes were the 30-days ending 22 February, 26 March and 4 December. The worst 30-day period for fatal crashes (24 fatal crashes in the 30-day period ending 22 February) is 53% higher than the lowest 30-day period (15.7 fatal crashes in the 30-day period ending 27 September). The worst 30-day period for casualty crashes (1282 casualty crashes in the 30-days ending 6 March) is 28% higher than the lowest 30-day period (1000 casualty crashes in the 30-days ending 22 January).

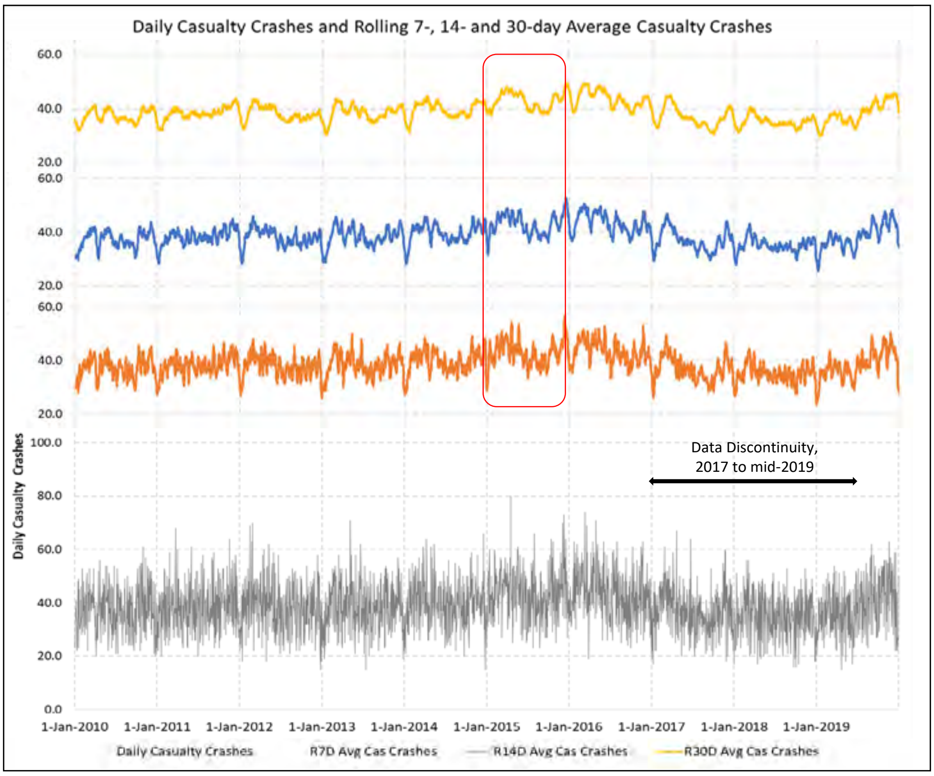


Figure 10. 10-year average daily casualty crashes, 2010 to 2019 including rolling 7- (bottom), 14- (middle), and 30-day (top) averages

The 14-day totals and 7-day totals, whilst having some similarities to the 30-day totals, show a clearer picture of the cyclic nature of crashes with much greater variability between highest and lowest periods without the lag effect of 30-day totals which peaks a period of time after the crash events have occurred. The rolling 7-day and 14-day smoothing shown in Figures B1 and B2 (Appendix B) can provide a solid basis for scheduling road safety campaigns, which would be considerably different to current practices, requiring a focus on risks identified in these reports.

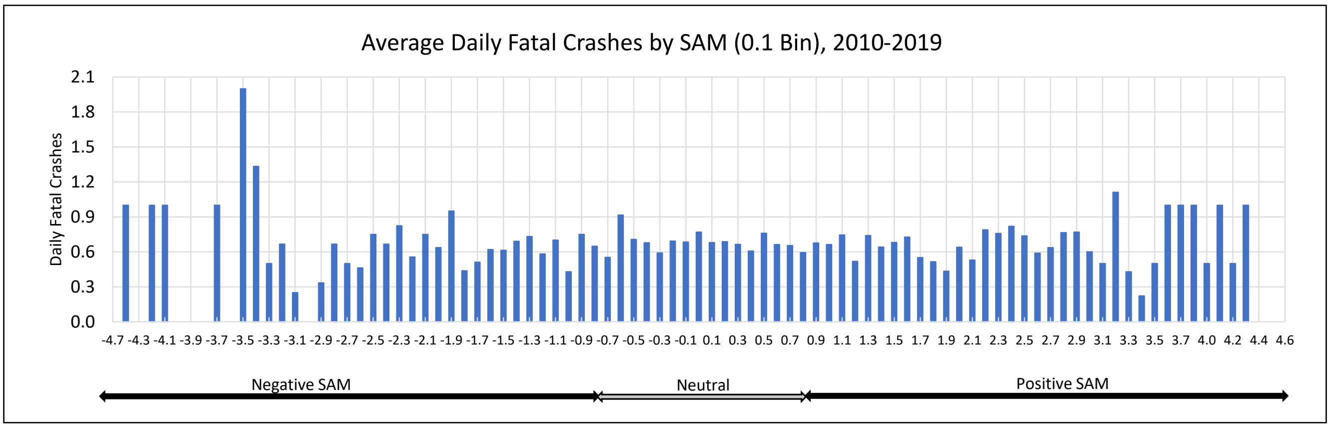
As shown in Figure 10, cyclic patterns do not align with years and generally the trends can last for three to six months or 12 to 18 months or more. For example, 2015 had a wetter/cooler late summer/autumn (February to May) with higher crash numbers. This was followed by a drier late winter/early spring (August to September) with lower crashes numbers. An unseasonal anomaly (warm and sunny spike) in mid-November to mid-December resulted in increased crashes.

Preliminary Statistical Analysis

Preliminary statistical analysis of the relationships between climate drivers and crashes was undertaken. There are complexities and limitations that need consideration and involvement of meteorological and road safety experts when analysing multi-variant impacts of climate drivers on crash occurrence, including:

- Weather and climate are the result of combinations of multiple metrics (cannot be fully explained by a single metric) and their effect on economic and human activity.
- Interactions between climate drivers – one can strengthen or weaken the effect of another.
- Seasonal effects of SAM (summer/winter) and IOD (winter/spring).
- Increased number of crashes or variability, occurring at extreme climate driver values, well beyond the BOM's definitions of normal, positive, and negative.
- Low fatal crash numbers, affecting the power of statistical tests to detect significant effects.

Plots of average daily fatal and casualty crashes versus SAM, IOD and SOI are shown in Figures 11 to 13. Visual inspection shows more variability of fatal crashes at extreme values of SAM, IOD and SOI and more variability of casualty crashes at extreme values of SAM and IOD. With SOI, casualty crashes are higher at negative values (El Nino, drier than normal) but trend down as SOI moves towards neutral and positive. Drier weather (particularly in winter) may increase human activity and hence exposure, and can result in dew at night (clear skies), making roads slippery. With SAM's different seasonal effects, much of the variability in crashes at the extremes occurs in summer and winter months.



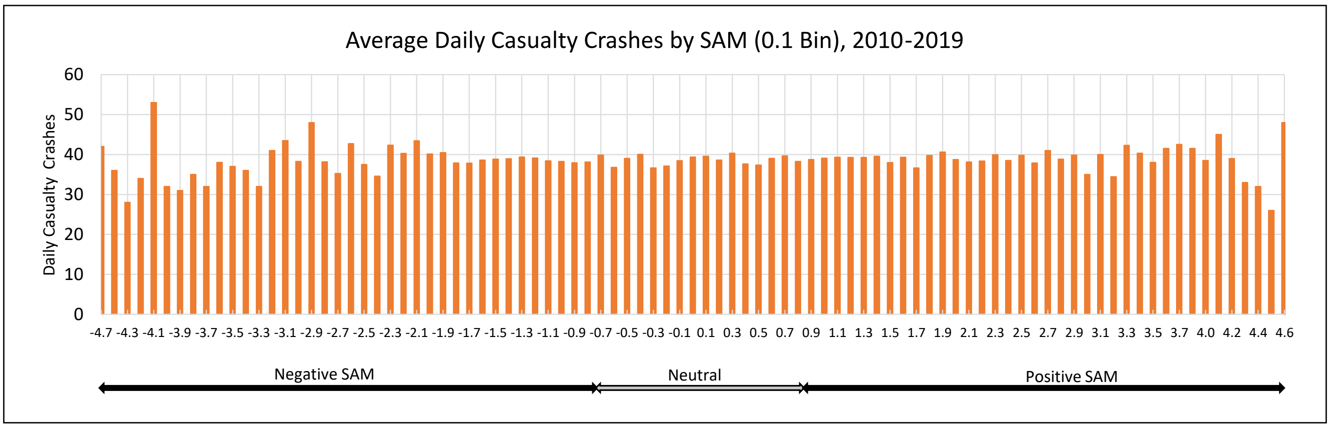
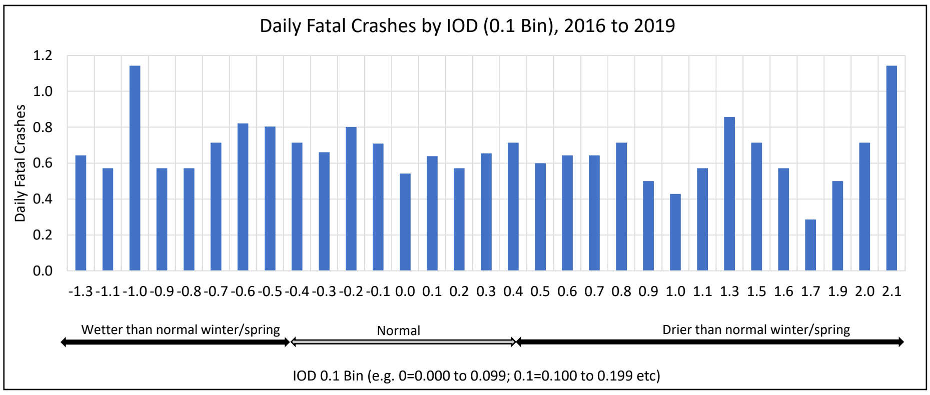


Figure 11. 10-year average daily fatal and casualty crashes by SAM 0.1 Bin, 2010 to 2019



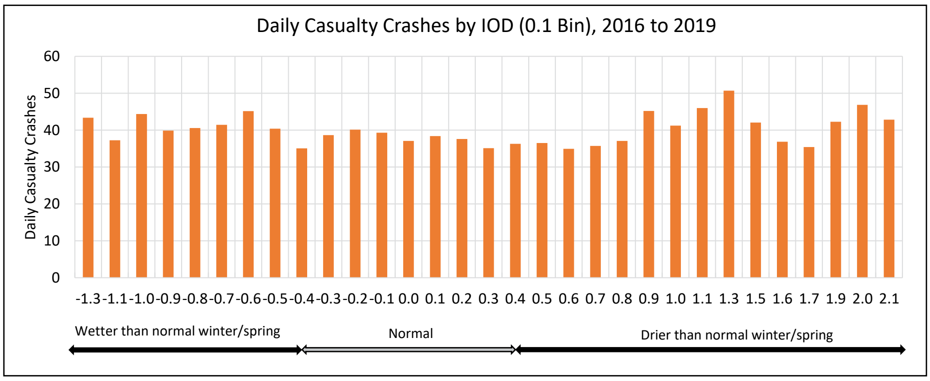


Figure 12. 10-year average daily fatal and casualty crashes by IOD 0.1 Bin, 2016 to 2019

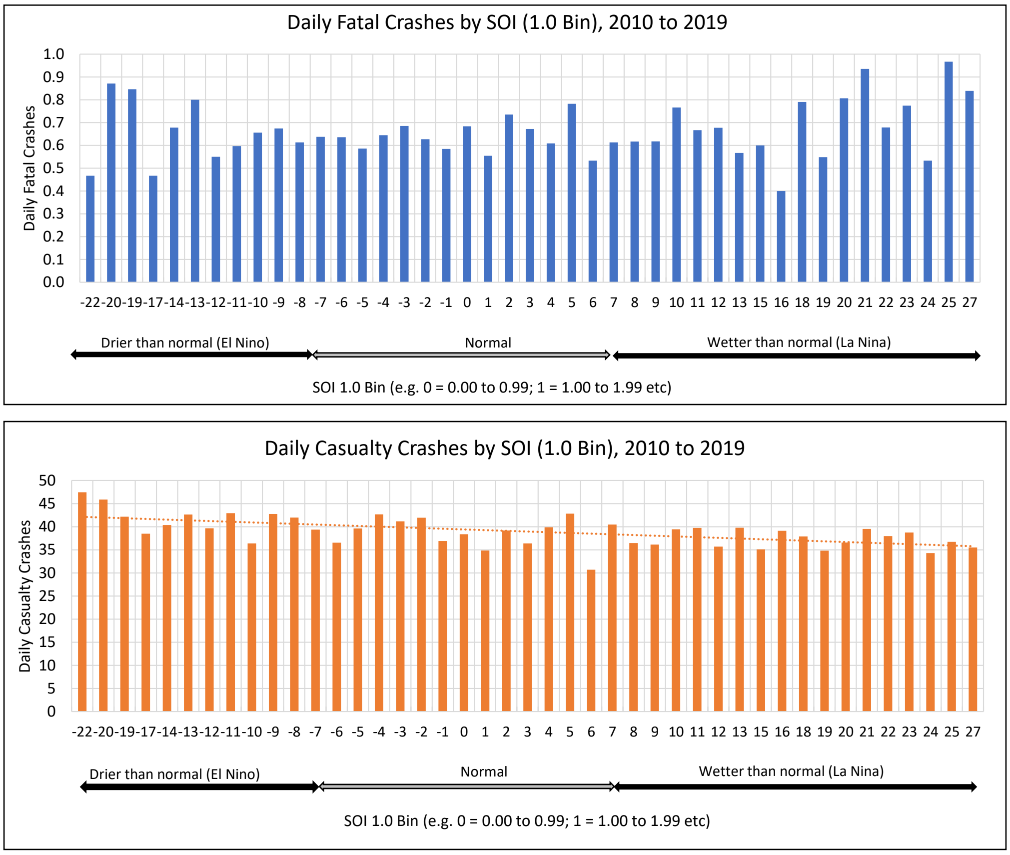
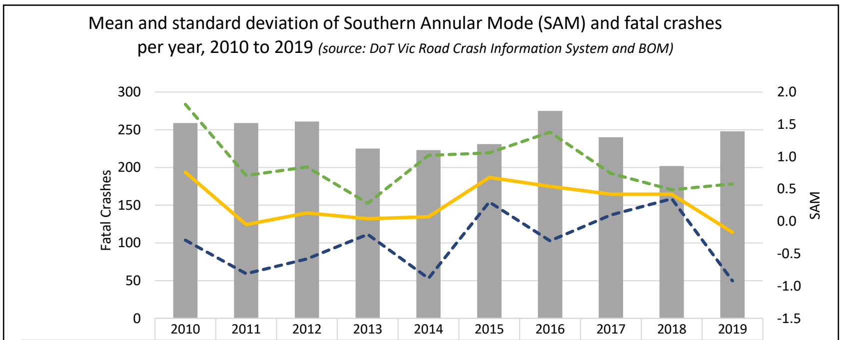


Figure 13. 10-year average daily fatal and casualty crashes by SOI 1.0 Bin, 2010 to 2019



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Annual fatal crashes	259	259	261	225	223	231	275	240	202	248
Average SAM	0.76	-0.05	0.13	0.04	0.07	0.68	0.54	0.42	0.42	-0.17
Std dev. upper bound	1.81	0.71	0.84	0.28	1.02	1.06	1.38	0.74	0.49	0.58
Std dev. lower bound	-0.29	-0.81	-0.58	-0.20	-0.88	0.30	-0.30	0.10	0.35	-0.92

Figure 14. Annual variation in fatal crashes and average SAM, 2010 to 2019

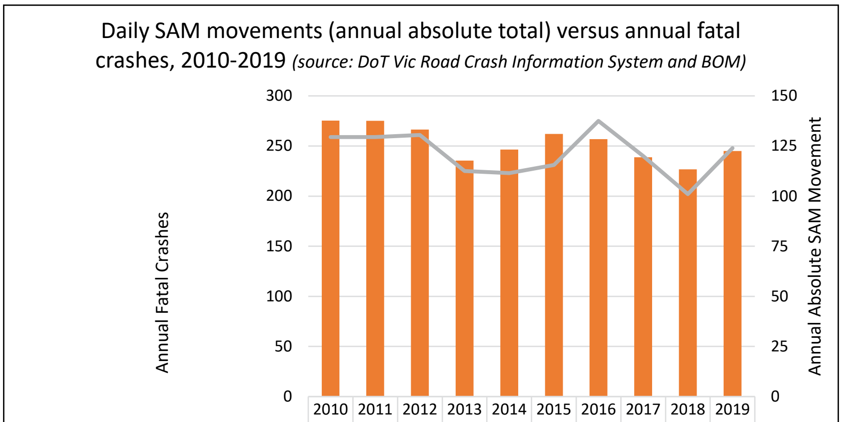
A Chi-Square Goodness-of-Fit Test was applied to the data and showed a statistically significant association (at the 0.05 significance level) between casualty crash numbers and each of the climate drivers (see Table 1). For fatal crashes, however, there was no statistically significant association, likely due to low numbers and randomness of fatal crashes.

Observations of SAM in Relation to Crashes

Figure 14 shows annual variations (2010-2019) in fatal crashes, ranging from 275 (in 2016) to 202 (in 2018). Daily SAM standard deviation values were very narrow in 2018 (an outlier year in terms of fatal crashes and daily SAM movements for this decade). This implies more stable weather conditions, particularly in the number and/or strength of cold fronts. Climate drivers and their collective

Table 1. Results of Chi-Square Goodness-of-Fit Tests (0.05 significance level)

Crash Severity	Climate Driver	DF	N	Chi-Square Statistic	p-value	Statistically Significant Association? (0.05 significance level)
Casualty	SAM (binned into 0.1)	90	141,797	161.82	< .0001	Yes
Fatal	SAM (binned into 0.1)	90	2,423	76.09	.852	No
Casualty	IOD (binned into 0.1)	12	15,788	55.79	< .0001	Yes
Fatal	IOD (binned into 0.1)	12	271	8.69	.729	No
Casualty	SOI (binned into 1.0)	42	141,797	640.14	< .0001	Yes
Fatal	SOI (binned into 1.0)	42	2,423	46.98	.276	No



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
SAM annual abosolute movement (total)	137.7	137.6	133.2	117.7	123.2	131.0	128.5	119.4	113.3	122.5
Annual fatal crashes	259	259	261	225	223	231	275	240	202	248
Positive or Negative SAM phase	68%	66%	62%	48%	51%	56%	65%	48%	52%	62%
Neutral SAM phase	32%	34%	38%	52%	49%	44%	35%	52%	48%	38%

Figure 15. Annual fatal crashes and annual absolute (total) SAM movements, 2010 to 2019

influences tend to follow a continuum not aligned with months or years requiring further statistical testing.

Figure 15 shows absolute SAM movements. Larger movements over the year indicate more variable day-to-day weather. Observation suggests movements away from neutral correspond with higher fatal crash numbers. The more varied SAM is, the more changeable the day-to-day weather is across the year, appearing to correspond with fluctuations in annual fatal crash numbers. For example, 2013, 2014 and 2018, with lower annual fatal crash numbers, spent around 50% of the year in the neutral phase. The years (2010, 2011, 2012, 2016 and 2019) with more than 60% in the positive and negative phases (exhibiting greater variation in weather) had higher fatal crash numbers. The transition years (2015 and 2017) with rising and falling fatal crash numbers lie between these extremes in SAM.

Comparison of Fatal Crashes between 2018 and 2019 in Relation to SAM Movements

Further investigation of 2018 versus 2019 showed most of SAM's variability occurred in the first six months of the year, with the sum of absolute changes being 53 in 2018 and 66 in 2019. This 25% difference in movements indicates weather was likely to have been more variable in the first six months of 2019 (where fatal crashes were much higher) compared to the first six months of 2018. The second six months had a similar sum of absolute movements between the two years (57 in 2018 and 60 in 2019) and the fatal crash numbers were similar too. Due to complexities of SAM having different effects in different seasons, combined with the effects of the other climate drivers, further work is required to investigate its influence on fatal crashes, including statistical testing with rolling 7/14/30-day comparisons.

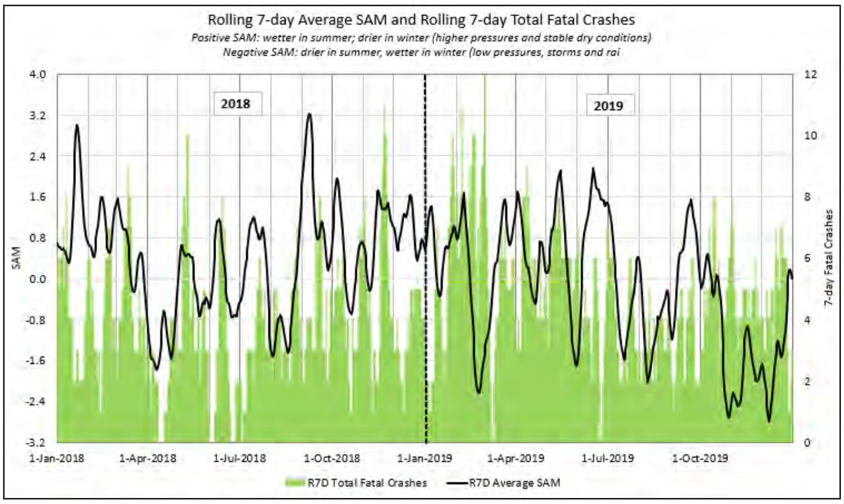


Figure 16. Oscillations of fatal crashes and SAM (showing rolling 7-day averages), 2018, 2019

Figure 16 shows rolling 7-day fatal crashes and rolling 7-day average SAM for 2018 and 2019. There is some correspondence in oscillations between fatal crashes and SAM in terms of timing, but not necessarily magnitude as there are other complexities in weather manifestations that affect crash risk. SAM does not have a constant influence on weather over the year. Its effect varies between summer and winter in relation to air pressures and wetter and drier conditions, resulting in considerable variation in day-to-day weather.

The following provides a comparison between SAM and fatal crashes for 2018:

- January 2018 to April 2018. Positive SAM in January (corresponding to a wetter period) moved into a normal phase in March and then to a negative phase in April. Although this coincided with a lower number of fatal crashes, SAM generally has less impact in autumn. With rain, it is the exposure to and timing of rain events in relation to road user exposure (peak period versus 3am) rather than the amount of rain that affects crash risk (Stevens et al., 2019). April 2018 had fewer large rain events compared to April 2019 which had many small rain events including widespread afternoon/evening thunderstorm activity. In April 2019 there were 15 more fatal crashes than in April 2018.
- June and July 2018. SAM resulted in normal and/or dry conditions. Fatal crash numbers were low.
- Late July 2018. SAM moved from a neutral phase into a positive phase (corresponding to wetter conditions), coinciding with a higher number of fatal crashes, although below the 10-year average.
- September and early October 2018. SAM was in a positive phase (corresponding to wetter conditions) where fatal crash numbers were higher than the 10-year average.
- Mid-November and mid-December 2018. SAM was in a positive phase (wetter conditions), with higher fatal crash numbers (higher than average in November 2018).

Whilst daily variations in SAM were quite different in 2018 compared to 2019, there was some correspondence between fatal crash numbers and movements in SAM in 2019 as well. For example:

- Late January 2019, early February 2019 and early May 2019. Wetter periods, with above average fatal crash numbers.
- February 2019. Drier than normal, with a higher number of fatal crashes. One explanation was that extreme daytime temperatures had a negative impact on crashes as it contributed to melting pavements, heat stress and fatigue, apparent with increased afternoon fatal crashes. Cooler nights (high dewpoint) resulting in damp (slippery) pavements overnight and in the early morning. These corresponded with the timing of crashes from mid-afternoon and overnight in 2019 (see Figure 18).
- June 2019, mid-October to mid-December 2019. Drier periods with generally less fatal crash numbers. However not all dry and wet periods immediately corresponded to low and high fatal crash numbers respectively, indicating there are other factors involved, including the lag effect where weather can influence conditions for many days, weeks, and months after the event. For example, after an extended period of heavy rain, the water catchments and ground remain damp for long periods creating a damp road environment and visibility issues (increased cloudiness).

It may not be just absolute values of SAM that are important to crash risk, but the slope (strength) of day-to-day fluctuations with extreme values of SAM at certain times of the year (seasons). Rapidly changing weather conditions may catch road users out particularly when

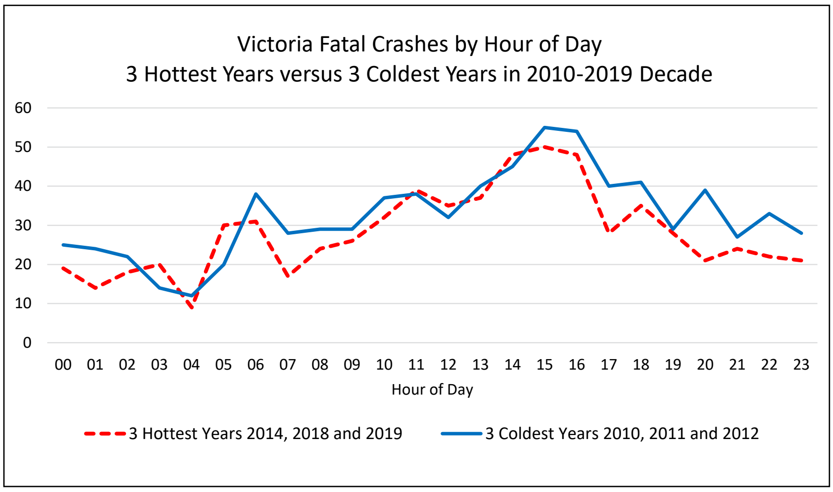


Figure 17. Comparison of distribution of fatal crashes during the three hottest years (2014, 2018, 2019) and the three coldest years (2010, 2011, 2012) in the 2010 to 2019 decade

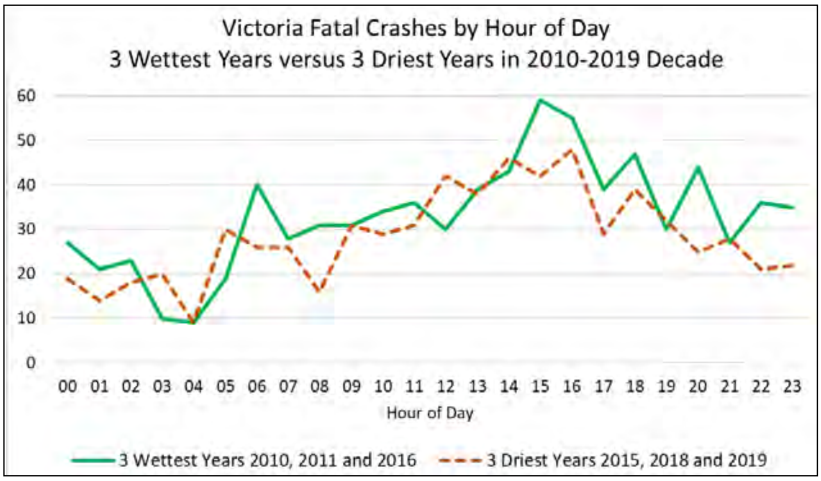


Figure 18. Comparison of distribution of fatal crashes during the three wettest years (2010, 2011, 2016) and the three driest years (2015, 2018, 2019) in the 2010 to 2019 decade

moving from a dry period to suddenly wet or from a warm period to suddenly cold. Other climate and weather drivers, such as SOI and IOD, can either strengthen or weaken the weather effects of SAM. Further research is required to test relationships between crashes and climate drivers, requiring expertise in meteorology as well as in road safety. Greater understanding will likely emerge when daily, hourly and minute data, and their spatial relationships with crashes, are investigated.

Weather-related influences on the hourly distribution of fatal crashes

Figure 17 shows the distribution of fatal crashes by hour of day in the three hottest years (2014, 2018 and 2019) and the three coldest years (2010, 2011 and 2012). There were 106 (16%) more fatal crashes in the three coldest years compared to the three hottest years. The additional crashes mainly occurred overnight, early morning and morning peak, consistent with damp pavement and lower visibility conditions, cold tyres, and cold brakes occurring on cold nights (due to ice, frost, fog, mist, dew, and morning sun-glare).

Figure 18 shows the three wettest years (2010, 2011 and 2016) compared to the three driest years (2015, 2018 and 2019). There were 112 (16%) more fatal crashes in the wettest years compared to the driest years. The marked jump in fatal crashes across both morning and afternoon peak periods, especially at 6am and 3pm, is consistent with heavier demand periods when short headways provide less space for errors. In the afternoon peak especially, road users are more fatigued (work/activity related as well as driving hours; Kononov, Reeves, Durso & Allery, 2012). This is critical when it coincides with wet road conditions, where braking distances increase due to reduction in pavement friction and lower visibility can delay reaction times. Higher crashes also occur overnight. Both wet and cold weather conditions are often accompanied by slippery roads and poor visibility (through the windscreen and external to the vehicle). For example, shiny mirror road surfaces enhance headlight backscatter and create visual distortions (reflections from both old and new pavement markings and road repairs).

Comparison of Fatal Crashes in 2018 and 2019

As seen in Figures 14 and 15, 2018 was an anomaly year with respect to long-term absolute movements and variation of SAM indicating 2018 had more stable and less varied weather patterns. Although 2019 had a higher number of fatal crashes compared to 2018, the main differences occurred in early months, i.e., a difference of 50 fatal crashes between 2019 and 2018, with the largest state-wide increases in February (+17), April (+15), May (+8) and June (+6) - see Figure 19. Noticeably in 2018 four of the months had exceptionally low fatal crashes with April 2018 having the lowest monthly fatal crashes since records began in 1952 (much less than half the average) with only eight fatal crashes state-wide. February (14), June (12) and July (14) were also historically low months in 2018. April 2018 had unseasonable weather, the hottest on record with very dry conditions and warm nights. During 2019 increases generally occurred both in metro and country areas but were more pronounced in one or the

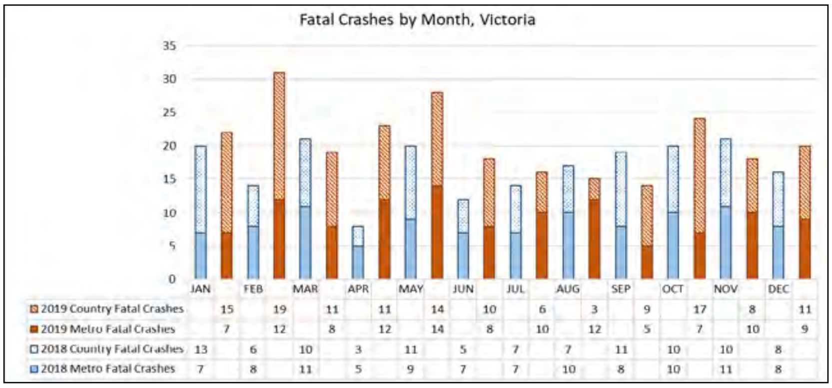


Figure 19. Monthly distribution of fatal crashes, Victoria split by Metro and Country, 2018 compared to 2019

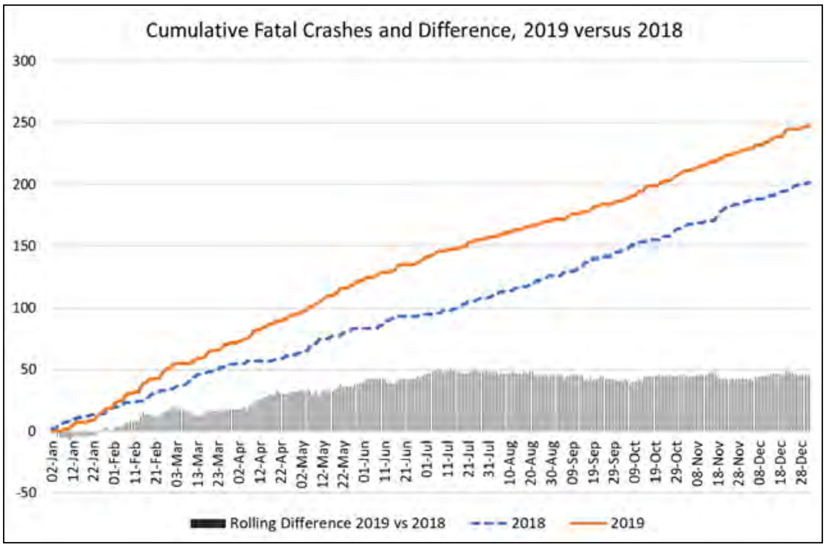


Figure 20. Victorian fatal crashes (cumulative) and differences, 2019 compared to 2018

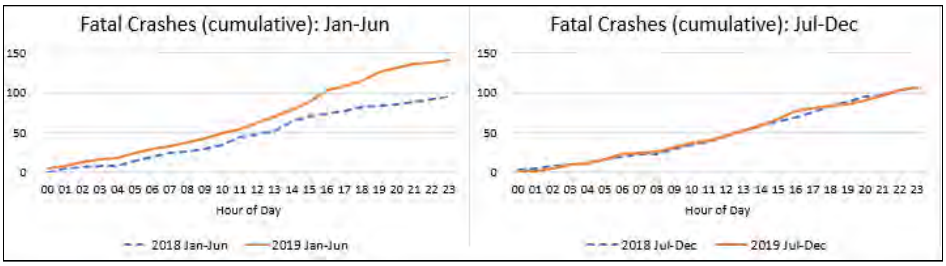


Figure 21. Victorian fatal crashes (cumulative), 2019 compared to 2018

other in different months compared to 2018. It is worth highlighting that the centroid for 2019 fatal crashes was much further west than in 2018 (see Figure 3).

The first six-month period (specifically 25 January to 6 July, as shown by the rolling difference in Figure 20) shows a large shift in hourly distribution of crashes over the day compared to the later six months (see Figure 21). In the second half of the year (from 7th July 2019 onwards), fatal crash numbers were very similar to 2018. From July to December 2019, the hourly distribution of crashes was also very similar to 2018. These indicate other factors are involved in crashes besides randomness or normal variation.

Weather Comparisons of First and Second Six Months of 2018 and 2019

Figure 22 shows a range of weather metrics (rainfall deciles, maximum temperature deciles, minimum temperature deciles, mean temperature deciles, solar exposure (radiation), and water vapour pressure at 9am and at 3pm for the first six months and second six months of 2018 and 2019. There were considerable variations between 2018 and 2019, both in the first half and second half of the year.

The first six months of 2018 were drier (most of Victoria “very much below average” or “lowest on record”) compared with the same period in 2019 (“average” to “below average”), especially in areas where travel demand is highest (particularly to the west of Melbourne, as shown on the rainfall maps, which includes major regional

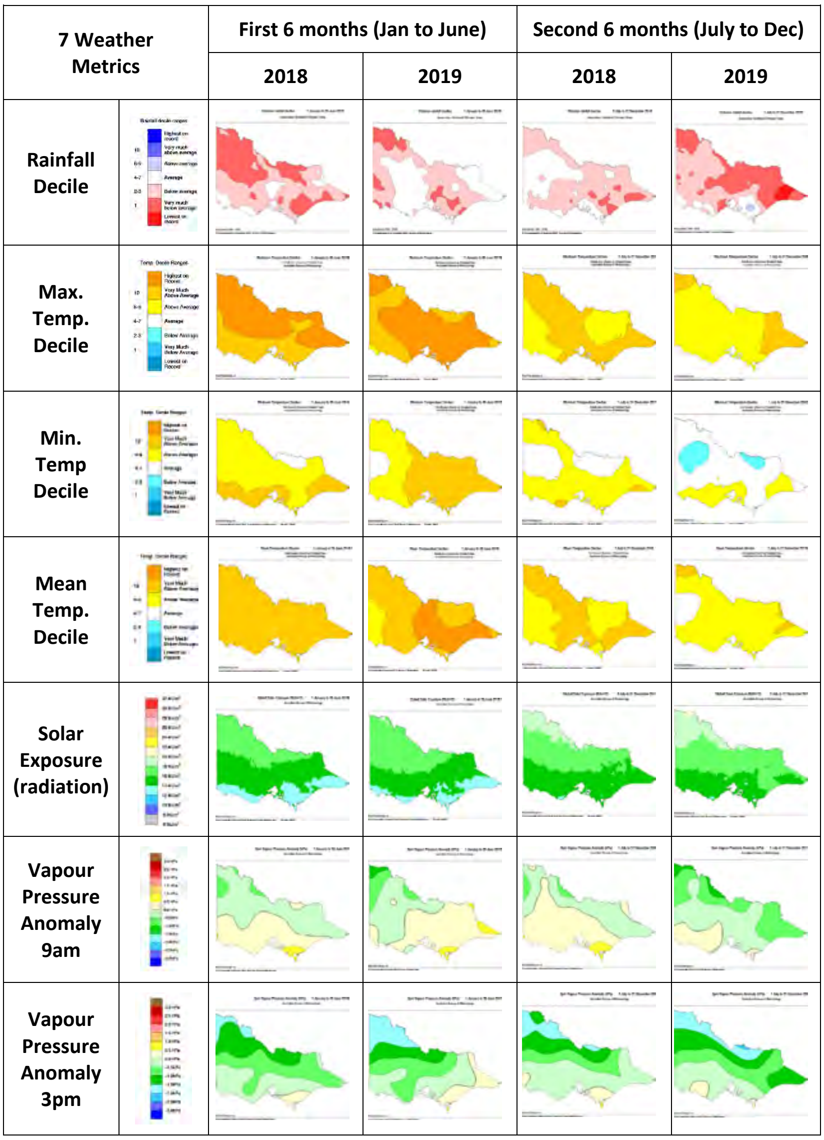


Figure 22. Comparison of seven weather metrics for first and second six months of 2018 with 2019 (compiled from BOM n.d.)

centres). This is consistent with the movement in the centroids discussed earlier.

In the first six months of 2019, compared to 2018:

- The maximum temperature was warmer in the south of the state, where travel demand is high.
- The warmer temperature towards the south in 2019 was also reflected by increased solar radiation.
- The minimum temperature was warmer in the centre and east of the state, being "very much above average".
- The mean temperature in the centre and east of the state in 2019 was "the highest on record".
- The vapour pressures were higher, particularly in northeast Victoria, meaning there was more moisture held in the air which can turn into dew overnight when night-time temperatures fall (further analysis of dewpoint is needed as higher dewpoint temperatures can make roads unseasonably slippery in summer months).

The second six months were different with 2019 being closer to average but drier than 2018:

- 2018 was "average" or "below average" whilst 2019 was "below average" to "very much below average" in terms of rainfall in the east, with some being the lowest on record.
- The weather trends tended to reverse in the second six months, with 2018 being warmer in the day and night compared to 2019.
- In 2018 there were higher vapour pressures, primarily in the morning.

It is not necessarily absolutes or averages in metrics that are important for measuring crash risk, but day-to-day variability of weather and the effect of various metrics combined. When certain weather events occur, consideration is needed of what is normal for that time of the year, the temporal relationships with human activity and traffic demand across the day or week, and the geographical location. For example, a hot dry summer's day may have an adverse effect on crashes whereas a warm late winter/spring day may be favourable for driving conditions. Moisture held in the air (vapour pressure) or cloud, influences visibility, noticeably during daytime. Its influence can be positive (reduced intensity of sunlight resulting in less sun-glare) or negative (reduced visibility through thick cloud creating heavily overcast conditions). At night air moisture influences pavement conditions either positively (cloud cover keeps air warm and pavements dry) or negatively (absence of cloud can result in cold conditions with moisture settling as dew/frost, and/or low cloud results in mist/fog). Clear skies increase sun-glare around dawn.

Other important metrics likely contributing to crash risk include barometric-pressure, wind-speed, dewpoint, and relative-humidity. These vary daily and hourly, hence it is the variations that influence crash risk. For example, a warm day with a cooler night leading to dew or frost, or the number of rainfall events over the month (several large rain events may have a lower safety risk compared to many light showers or afternoon/early evening thunderstorms) create conditions which surprise roadusers.

Comparison of Monthly Weather and Crashes for April 2018 and 2019

A high-level comparison of April 2018 versus April 2019 is shown in Figures C1, C2 and C3 in Appendix C. April was chosen as it had much higher fatal crashes in 2019 (23 fatal crashes/24 fatalities) compared to 2018 (8 fatal crashes/9 fatalities, 58% lower than the 10-year average of 19 fatal crashes). Seven of the fatal crashes occurred at night in 2019 compared to two in 2018, and eight occurred in the afternoon (1pm to 6pm) in 2019 compared to four in 2018.

These figures show mean maximum temperature (°C), mean minimum temperature (°C) and total rainfall (mm), with monthly values and deciles, together with their daily values. These are only three meteorological metrics and when other metrics are considered such as wind speed, cloud cover, air moisture, and solar radiation, the minute-to-minute variations reveal additional levels of complexity. Some differences include:

- Mean maximum temperature (Figure C1). Both April 2018 and April 2019 were warm months compared to the average, but April 2018 was unseasonably warm, being the highest on record. April 2019 had cooler daytime temperatures, although still much warmer than usual for April.
- Mean minimum temperatures (Figure C2). April 2018 was very much above average in the east whilst April 2019 was average in the west. Elsewhere in both months the mean minimum temperature was above average. Overall, April 2019 had cooler night-time temperatures, with larger differences between daytime and night-time temperatures.
- Total rainfall (Figure C3). April 2018 was dry with much of Victoria "below average", and drier in the centre south and southeast. April 2019 was also dry, with much of Victoria "very much below average", and drier in the centre, west and northeast. Overall, April 2019 was drier compared to April 2018.

Although monthly values may appear similar, it is the variation of these measures occurring daily or even within a single day that is important. For example, on two days there may be similar maximum and minimum mean temperatures, but rainfall may only be present on one of those days. Even if the amount of rainfall is similar, if it falls at a different time of day (night-time on one day compared to daytime peak hours on another day when road usage is high) the effect on crash risk can be markedly different. The amount of rain received in a month may occur in a few heavy short-lived events where pavements dry out rapidly or occur as persistent drizzle over many days where pavements remain damp, with different impact on crash risk. It is important to look temporally and spatially at daily/hourly variations to improve understanding.

Day-to-Day Variation in Weather and Crashes for April 2018 and 2019

Figures C1, C2 and C3 show the differences in maximum temperature, minimum temperature, and rainfall for the individual days in April 2018 and 2019:

- April 2018 had several much warmer days (the highest on record in the north and very much above average elsewhere) compared to 2019, particularly for the first 13 days and for days 19 to 24. In April 2019 there were a handful of warmer days scattered throughout the month. April 2018 had many more (unseasonably) extreme days in terms of maximum temperature whilst April 2019 overall had many additional cooler days.
- In terms of night-time temperatures, April 2019 was closer to normal, with some cold nights apparent, whereas April 2018 had mainly warmer nights except towards the end of the month, as distinguished by the amount of dark blue, grey or pink shown on the maps in Figure C2. Cold nights can trigger dangerous road conditions (fog, frost, ice and dew).
- April 2018 was less dry than April 2019. However the rain primarily came in a single sequence from day 14 to 17 whilst in 2019 there were quite a few periods of light rain.

In understanding weather and its impacts on crash occurrence, it is necessary to understand the timing of various weather events in relation to human activity and road use. For example, a major thunderstorm and rain event occurring at midnight on Sunday night will result in a different crash risk compared to a similar event occurring during peak hours on a Friday night. The temporal nature of weather needs to be investigated as many events may only last for only a matter of hours or even minutes (peak wind gusts and thunderstorms) and can be limited to small geographical areas or be short-lived. This can provide an element of surprise for road users, increasing crash risk (usually not recorded in crash records).

Summary and Conclusions

The long-term annual variations in climate and weather in relation to rainfall, minimum and maximum temperature and the BOM annual commentaries show marked differences between years. When the wettest years were compared to the driest years and the hottest years were compared to the coolest years, there were clear and logical time-shifts in fatal crash distributions over the 24-hour day. Fatal crashes increase in colder and wetter years, particularly overnight and during peak periods.

The three primary climate drivers affecting Victoria were shown to have cyclic/oscillating phases varying from weeks to many years. Understanding how the longer cycles (IOD and SOI) interact with SAM's typical two-week cycle is necessary to assess road crash causation and risk. These climate drivers have three distinct phases: positive; negative and neutral influencing weather manifestations differently. There is a statistically significant association between casualty crashes and each of the three climate drivers (Chi-Square Goodness-of-Fit Test), suggesting that a relationship exists between crashes and climate. There is more variability in fatal and casualty crash numbers at the extreme values of the climate drivers with the exception of SOI where casualty crash numbers decrease as SOI moves across the entire range from negative to positive.

Fatal and casualty crashes were shown to have cyclic/oscillating natures, varying within each year in amplitude and cycle length. Smaller peaks and trough combine into larger longer-term trends (spanning months or several years) which are neither random, nor relating to traffic demands, holiday periods, or road safety campaigns for which climate provides a potential explanation. Averaging over the decade found some months had up to 44% more fatal crashes than others. Months (and years) are an artificial construct for analysing climate, weather, and road crashes. When rolling 30-day periods are used, variation increases to greater-than 50%. Shorter assessment periods, for example, one or two weeks, show greater variability over the decade. The cyclic nature of crashes provides a basis for targeting research and improved timing of road safety campaigns to align with actual high crash periods.

SAM has the greatest day-to-day influence on Victorian weather. SAM's variability both in terms of standard deviation and absolute movement, showed associations with fatal crash number variability (the more varied the weather in any year, the more fatal crashes). For SAM, 2018 was a standout year with low variability, primarily occurring in the first six months of the year.

In Victoria the apparent sudden rise in fatal crashes in 2019 (+46) compared to 2018 caused considerable concern. Limited explanations for the increase led to this research to assess whether climate and weather could provide a plausible explanation. When the daily movement of SAM was compared for 2018 and 2019, considerable differences were seen in the strength and variability over the year, especially in the timing and duration of wetter and drier periods. When fatal crashes were overlayed against SAM, associations were observed between SAM cycles and fatal crash cycles.

Closer examination of 2018 and 2019 showed the increase in fatal crashes occurred between 25 January and 6 July (50 more fatal crashes in 2019). Considerable differences in the strength and spatial distribution of weather metrics between the first six-months of 2018 and the first six-months of 2019 were noted, giving insights into how weather patterns might be influencing crash risk. Monthly and daily level of analysis revealed further details of the variability of weather patterns. For example, April 2019 had 15 more fatal crashes than April 2018, particularly in the hottest part of the day and at night. April 2019 was a month with extreme and unusual conditions, with colder nights (slippery roads) and more days with scattered thunderstorm activity (catching motorists by surprise) compared to April 2018. The biggest difference in weather variations occurred geographically and temporally.

Given that longer cycles of climate can influence crash risk, fatal crash trend analysis needs adjusting to account for annual and seasonal variations. For example, a minimum rolling 10-year period (two 5-year cycles) should be used to smooth out the influence of climate providing an improved picture of fatal crash trends. This analysis can be expanded to other jurisdictions. However each jurisdiction needs to understand their own local context in relation to climate, latitude, geography, and crash risk.

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Author Contributions

JG and EH conceived this manuscript, undertook the data collection, data analysis and manuscript writing. Both authors revised the manuscript critically for intellectual content and have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare that there is no conflict of interest.

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Appendix A

Southern Oscillation Index (SOI)

SOI has three phases – negative SOI (El Nino), positive SOI (La Nina) and neutral SOI which affect the weather in the east coast of Australia. SOI typically comprises a four-year cycle to move between the three phases. When SOI is negative for a sustained period it results in hot and dry conditions with increased risk of drought, higher temperatures and heatwaves, clear skies, colder nights, and longer frost season. When SOI is positive, there is more evaporation, more clouds and more rain resulting in colder weather, including floods and cyclones. The neutral (normal) phase, which occurs for more than half of the time, delivers normal rainfall in many parts of Australia. The transitions between negative and positive phases have an impact on the weather too.

Indian Ocean Dipole (IOD)

IOD has three phases – negative IOD, positive IOD and neutral IOD. It has a cycle of 3-5 years. In the negative IOD phase, due to wind intensity and warmer waters in the north of Australia, there is more rain and moisture in the atmosphere in southern Australia. A negative IOD phase results in above-average winter-spring rainfall. In the positive IOD phase, due to less cloud and moisture in the atmosphere to the northwest of Australia, there is often less rainfall and higher than normal temperatures in the southeast of Australia during winter and spring. In the neutral phase, temperatures are close to normal, resulting in little change to the Australian climate.

Southern Annular Mode (SAM)

SAM has three phases and typically has a 14-day cycle and its wet to dry impact varies between seasons. However, it is the combination of the three climate drivers that determine the actual climate and weather experienced in south-eastern Australia. For example, in the second half of 2016 the negative IOD phase combined with the negative to positive transition of SOI resulted in wetter conditions. SAM oscillated between negative and positive during that period. SAM's rapidly changing cycle is the most influential climate driver on weather variations in the south-east of Australia and its relationship to crashes.

Appendix B

Ten-year daily average fatal and casualty crashes (normalised to a 30-day month to account for varying number days in the months), were analysed to identify any underlying patterns (see Table B1). Although data

Table B1. Fatal and casualty crashes by calendar month, 2010-2019

Months with the **lowest** number of **fatal** crashes	September (16.1 fatal crashes) June (17.0 fatal crashes) April (18.5 fatal crashes)
Months with the **highest** number of **fatal** crashes	February (23.1 fatal crashes) May (22.1 fatal crashes) March (21.6 fatal crashes)
Months with the **lowest** number of **casualty** crashes	January (1061 casualty crashes) September (1094 casualty crashes) August (1114 casualty crashes)
Months with the **highest** number of **casualty** crashes	February (1276 casualty crashes) March (1260 casualty crashes) November (1222 casualty crashes)

Table B2. Rolling 30-day fatal and casualty crashes, averaged over 2010-2019

Periods with the **lowest** number of **fatal** crashes	30-days ending (or including) 27 September (15.7 fatal crashes) 30-days ending (or including) 30 June (17.0 fatal crashes) 30-days ending (or including) 22 January (17.2 fatal crashes)
Periods with the **highest** number of **fatal** crashes	30-days ending (or including) 22 February (24.0 fatal crashes) 30-days ending (or including) 26 March (22.1 fatal crashes) 30-days ending (or including) 4 December (22.1 fatal crashes)
Periods with the **lowest** number of **casualty** crashes	30-days ending (or including) 22 January (1000 casualty crashes) 30-days ending (or including) 1 October (1092 casualty crashes) 30-days ending (or including) 31 August (1110 casualty crashes)
Periods with the **highest** number of **casualty** crashes	30-days ending (or including) 6 March (1282 casualty crashes) 30-days ending (or including) 18 December (1269 casualty crashes) 30-days ending (or including) 13 May (1234 casualty crashes)

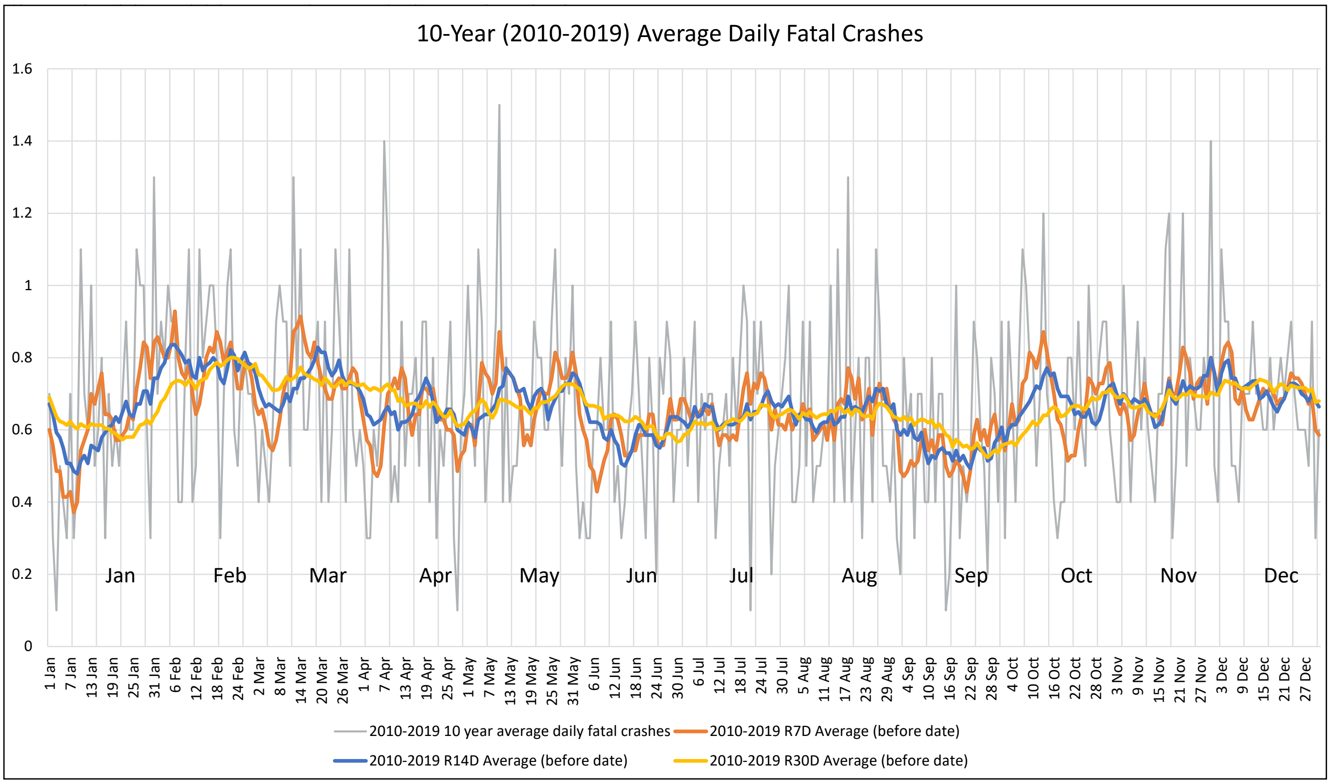


Figure B1. 10-year average daily fatal crashes, 2010 to 2019 including rolling 7-, 14-, and 30-day averages

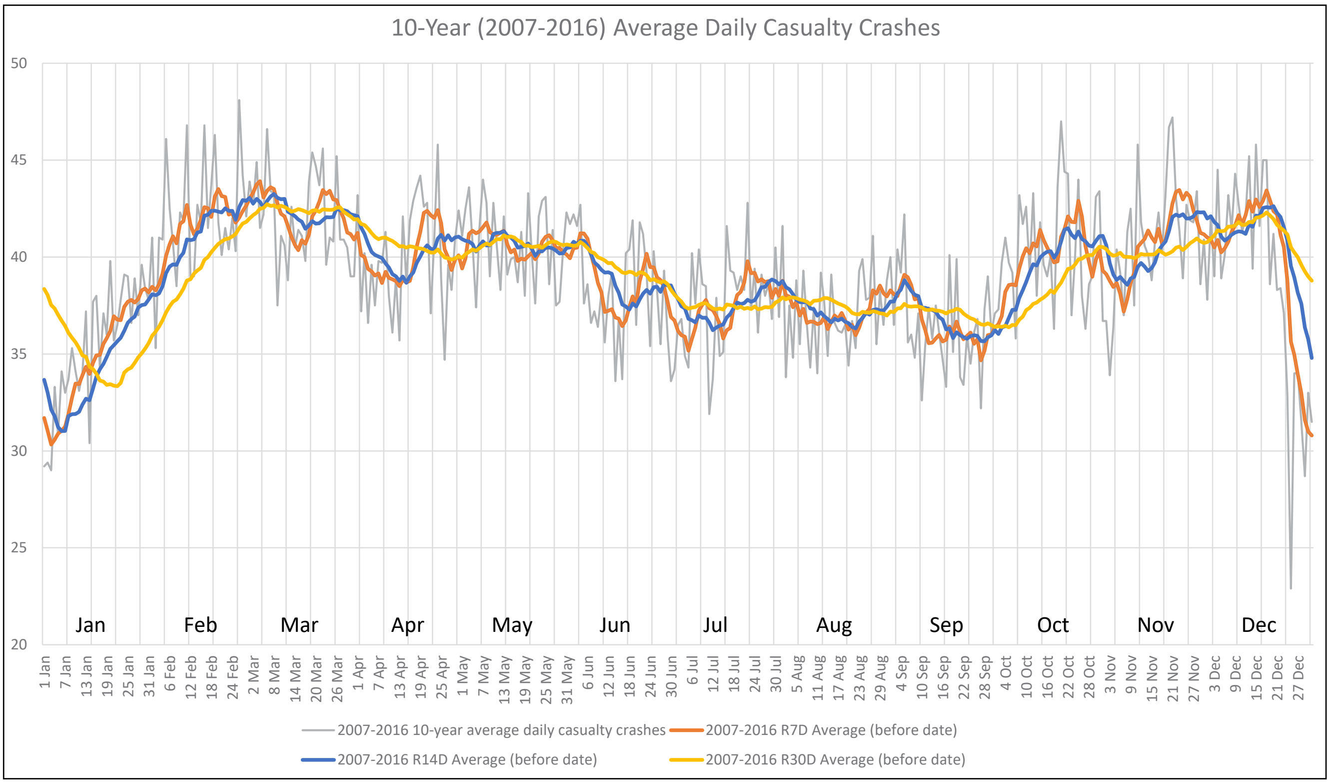


Figure B2. 10-year average daily casualty crashes, 2007 to 2016 including rolling 7-,14-, and 30-day averages

Appendix C

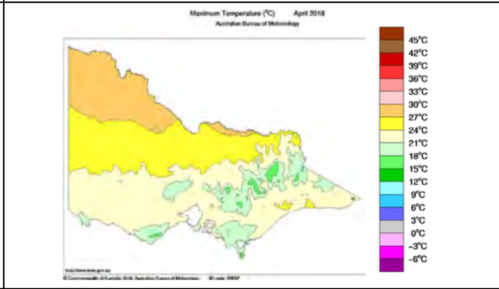
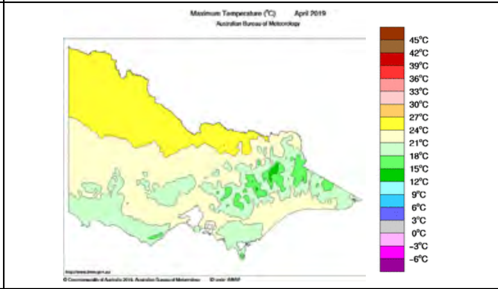
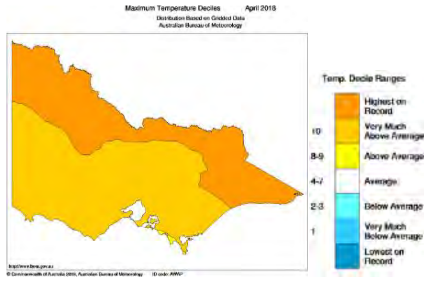
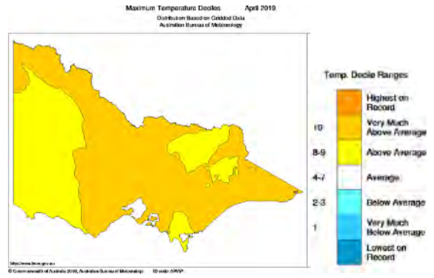
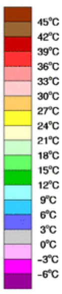
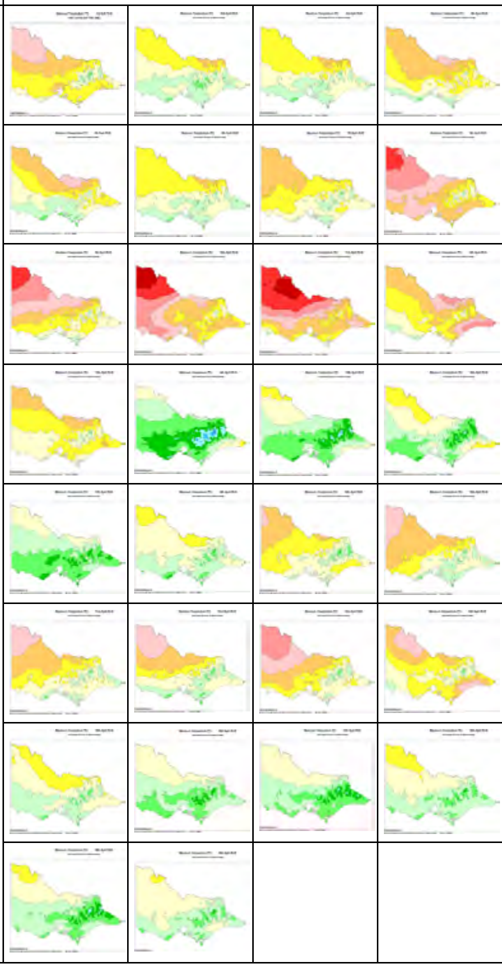
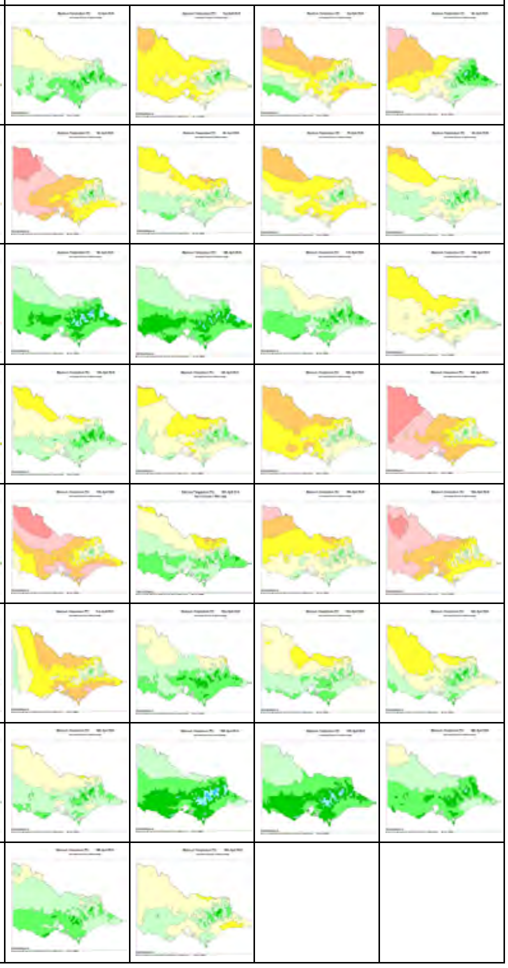
Metric	April 2018	April 2019
Mean Max Temp. (°C) 30 Day Average		
Mean Max Temp. Deciles 30 Day Average	 Highest on record or Very much above average	 Above average or Very much above average
Mean Max Temp. (°C) Daily (Days 1-4, 5-8, 9-12, 13-16, 17-20, 21-24, 25-28 and 29-30) 		

Figure C1. mean average maximum temperature by month and by day, and mean maximum temperature deciles by month, April 2018 compared to April 2019 (compiled from BOM, n.d.)

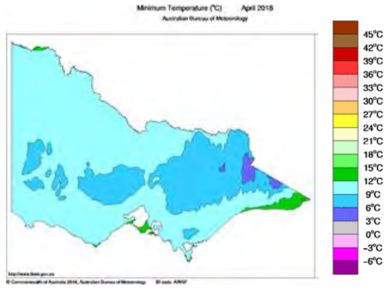
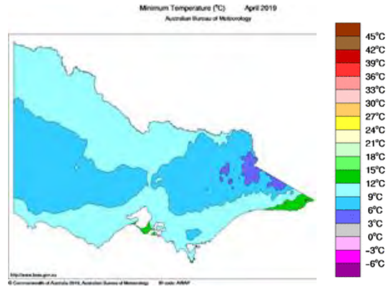
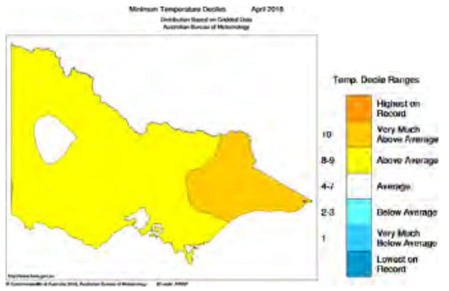
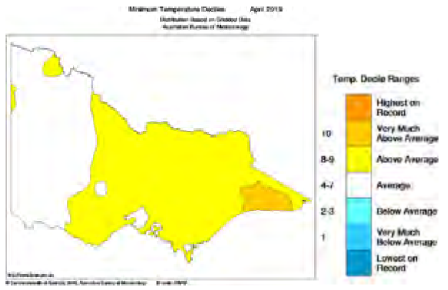
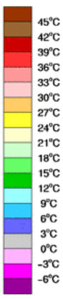
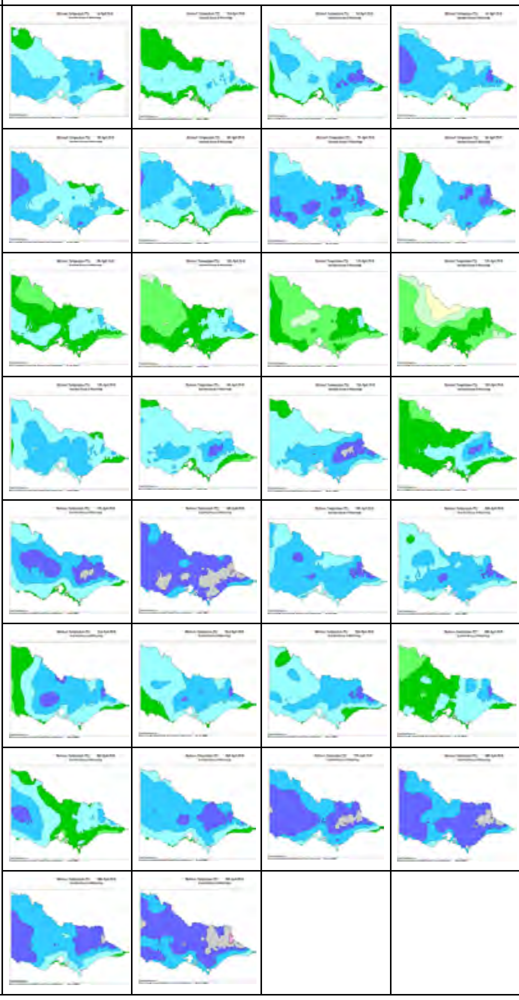
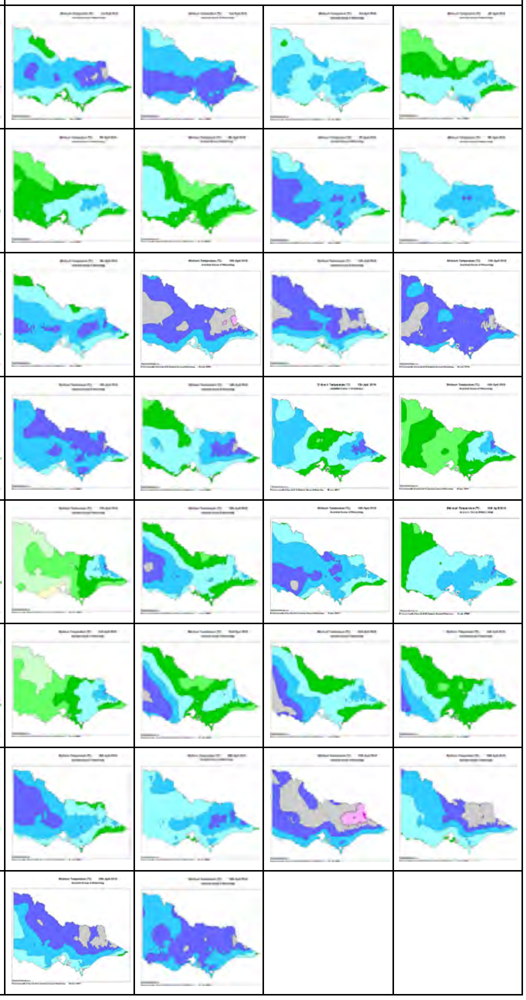
Metric	April 2018	April 2019
Mean Min Temp. (°C) 30 Day Average		
Mean Min Temp. Deciles 30 Day Average	 Above average & Very much above average in the east	 Above average & Average in the west
Mean Min Temp. (°C) Daily (Days 1-4, 5-8, 9-12, 13-16, 17-20, 21-24, 25-28 and 29-30) 		

Figure C2. Mean average minimum temperature by month and by day, and mean minimum temperature deciles by month, April 2018 compared to April 2019 (compiled from BOM, n.d.)

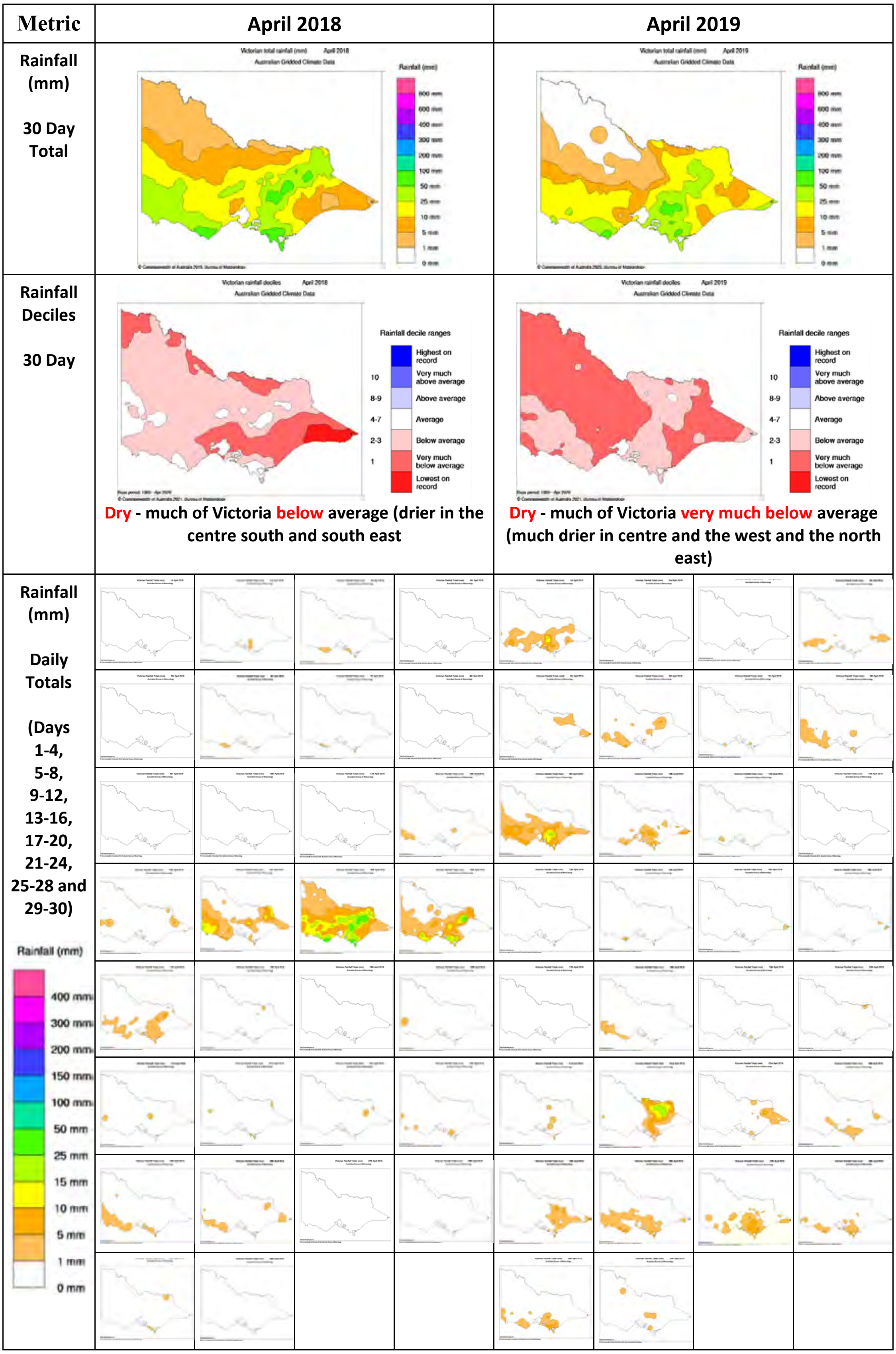


Figure C3. 30 Day average rainfall by month and day, and rainfall deciles by month, April 2018 compared to April 2019 (compiled from BOM, n.d.)