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ARTICLE

A Climatology of Heavy Rain and Major Flood Events in Victoria 1876-2019 and the Effect of the 1976 Climate Shift

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ABSTRACT

An extensive search has been carried out to find all major flood and very heavy rainfall events in Victoria since 1876 when Southern Oscillation (SOI) data became available. The synoptic weather patterns were analysed and of the 319 events studied, 121 events were found to be East Coast Lows (ECLs) and 82 were other types of low-pressure systems. Tropical influences also played a large role with 105 events being associated with tropical air advecting down to Victoria into weather systems. Examples are presented of all the major synoptic patterns identified. The SOI was found to be an important climate driver with positive SOIs being associated with many events over the 144 years studied. The 1976 Climate Shift and its influence on significant Victorian rainfall events is studied and negative SOI monthly values were shown to dominate following the Shift. However, one of the most active periods in 144 years of Victorian heavy rain occurred after the shift with a sustained period of positive SOI events from 2007 to 2014. Therefore, it is critical for forecasting future Victorian heavy rainfall is to understand if sequences of these positive SOI events continue like those preceding the Shift. Possible relationships between the Shift and Global Temperature rises are also explored. Upper wind data available from some of the heaviest rainfall events showed the presence of anticyclonic turning of the winds between 850hPa and 500hPa levels which has been found to be linked with extreme rainfall around the Globe.

1. Introduction

In 2017 [1] showed a marked fall in Victorian rainfall over the period 1986 to 2015 driven primarily by a reduction in the cool-season (April to October) rainfall. [2] in 2019 also addressed this problem. In this study a climatology of intense Victorian rainfall events since 1876 is presented to examine this change as well as identifying the weather systems involved along with their vertical structure and possible large-scale influences.

In this study we took advantage of a Victorian Government list of major floods available on the web: http://www.floodvictoria.vic.gov.au/centric/learn_about_flooding/flood_history/pre_1900_floods.jsp.

This list finished in 2007 and we added events after this from Bureau of Meteorology records after 2007. We then began a search for further events to account for possible omissions in the Victorian Government lists or potentially major impact events which didn't quite meet the River height criteria to be classed as major floods but had a

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huge impact. The main source of known impacts came from a search of the Archives of the Melbourne Argus, Melbourne Age and Gippsland Times and other Regional Newspapers which are available at https://trove.nla.gov.au/newspaper covering the period 1860 to 1957. The search also involved looking for events which were associated with record Victorian rainfall or widespread heavy rainfall (daily totals to 100mm or more). We also added to this group events classified as major from various Local Government Reports available on the web but not recorded in the SES list. From analyzing the impacts of these additional events, we selected the high impact events as unofficial major floods.

There are now two lists:

A list of all known events numbering 389 describing the impact and synoptic situation where possible.

This list was reduced to 319 strong impact events between 1860 and 2019 for the Victorian region.

A copy of the list can be obtained by emailing jeffjcallaghan@gmail.com .

Section 2 of this paper describes the various sources of data used in the Study. Section 3 illustrates the changes to river hydrology which is experienced over long periods using the Yarra River as an example. The method of rating floods is covered in Section 4 while a climatology of Victorian heavy rainfall and major flood events is examined in Section 5. This includes the role of the SOI and effects of the 1876 Climate Shift. Examples of synoptic weather types causing major flood events are provided in Section 6. The vertical structure of the heaviest rainfall events is examined in Sections 7 Mechanisms were described in Section 8 while a conclusion is reached in Section 9.

2. Data Sources

In this report we have used data from the Bureau of Meteorology and data from the National Centres for Environmental Prediction/ National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis Project, which were available at: https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html.

Early mean sea level pressure (MSLP) analyses were obtained from Bureau of Meteorology charts published in various newspapers, the earliest being from 1910 in the Sydney Morning Herald.

These can be found at https://trove.nla.gov.au/newspaper which we mentioned above as the main source of impacts. Prior to this an excellent record of Australian charts and detailed newspaper description of significant weather was created by the Meteorological pioneer Sir Charles Todd (Chief Astronomer of South Australia). These charts extend back to 1879 and can be found at www.charlestodd.net/Todd_Hi-Res/.

Earlier charts were created using official meteorological observations published in the newspapers at the time.

Of the 319 events list between 1876 and 2019 the following are the associated synoptic weather patterns:

East Coast Lows (ECL) 121

Low pressure systems 82

Tropical interaction: -

Troughs or fronts with tropical inflow 58

Lows with tropical inflow 31

Extra-tropical transition of a tropical cyclone (ET) -1

Strong NE winds 1

Tropical Lows 14

Total Tropical Interactions 105

Fronts 10

Trough 1

There has been a tendency for the occurrences of ECLs to increase since 1945. This was discussed in [3] Callaghan 2019 however with more intensive digging older ECL events were unearthed so the trend is still there but not as great. There were 51 ECL events from 1876 to 1944 (69 years). There were 34 ECL events from 1945 to 1976 (32 years) and 41 ECL events following 1976 (44 years) that is a total of 71 events in 76years. The year 1976 was marked by a Global Climate Shift (see below).

3. Changes to the Hydrology of Rivers over Time

River floods have been mitigated over the period of our study by increasing discharge rates through dredging and removing rock outcrops etc., and by building dams to store flood waters. This mitigation has been offset to some extent by an increase in urban runoff, caused by growth in urban areas, especially during the last forty years. Dams have been constructed throughout the study region.

As an example, below are documented changes to the Yarra River since 1849:

27-29 November 1849

A flood is exceeded by several feet any flood of former years. The weather-gauge at the Flagstaff (Melbourne) indicated a fall of 175 mm of rain on Tuesday 27 November 1849. Twelve people were drowned in the Yarra and Maribyrnong River floods. In Melbourne (CBD) at 1800 UTC 27 November the flood was at its greatest height. The wind and storm surge reports indicated that an intense low caused the floods. At Collingwood there was considerable wind damage with large trees, fences and chimneys blown down and at Williamstown a storm surge flooded farms to a depth of 60 cm. Serious flooding also occurred in Gippsland indicating the low moved east along the Victorian Coast.

1863 Flood

This flood is considered the largest on record. There was ten feet (3.05 metres) of water in the closed bar of the Sir Henry Barkly Hotel Richmond. At Hawthorn the river rose between thirty and forty feet (9.14 to 12.19 metres) higher than during the great flood in 1849. In the city the flood attained only a lesser height than in November 1849, however between 1849 and 1863 the river had been enormously deepened by artificial means, and thus a very much greater body of water could pass seawards than was the case at the period of the great flood of fourteen years earlier.

1891 Flood

At the Johnston Street bridge the water reached 41 ft (12.50 metres) above summer level. Mr. Ellery, the Government Astronomer at the time, concluded that the 1891 flood was a little higher, perhaps about 6inches (15.2 cm), than that of 1863 due to changes at Richmond discussed below.

Reduction of Flood Levels in 1891

Whatever damage was done by the 1891 floods it was at the time considered certain that it would have been far greater had it not been for the vast improvements in the river affected by the Harbour Trust. The trust undertook to make these improvements in 1887 and spent large sums of money with apparently excellent results. The Falls at Market Street in the City were entirely removed. This was a raised rocky causeway, which could be crossed in the summer months almost without wetting the feet, and it was converted into navigable water 16 ft (4.88 metres) deep at low tide.

Higher Levels at Richmond in 1891

The Floods Inquiry Board, appointed after the 1891 disaster came as a result of very careful investigation to the determination that the flood of 1891 was is in volume about two thirds of that of 1863 and yet at several points by comparison with such levels as still remained it was determined to have been higher than that of 1863. After much enquiry and doubt, the reasons for this were found in the fact that certain railway and road embankments, especially the approach leading to the Botanical Gardens bridge which had been completed since 1863, had thrown the water back on Richmond. The building of such masses of cottages and houses on the Richmond flat presented to the outpour of the water more obstructions which did not exist in 1863. All those were the reasons of the higher levels.

1901 Flood

William Davidson, inspector general of public works said in 1901 “If rainfall returns are any indication the water passing down the Yarra in 1901 was equal to the volume in 1863 and one third in excess of the volume in 1891. The 1891 flood the water rose to about 8ft (2.44 metres) in the bar of the Sir Henry Barkley Hotel in Punt road. In 1901 the water had 3feet (0.91 metres) to 3feet 6inches (1.07 metres) to rise to get to the floor of the bar. The flood level at that time was, therefore, at least 11 feet (3.35 metres) lower than at the maximum of the flood of 1891.” The reasons for the vast reduction of the 1901 flood levels resulted from the widening and deepening the river from Princes Bridge to a point beyond the South Yarra railway bridge which was recommended following the 1891 floods.

Between 1924 and 1929, the Melbourne and Metropolitan Board of Works removed 24,400 items of natural debris from the river to improve flood control and navigation. In 1929 a severe loop in the river at Burnley was eliminated by cutting a canal to make a straight, wide section. Herring Island was created in the process. The Yarra’s last great flood was the one in 1934 which reached 12.05 metres at the Johnston Street Bridge compared with 12.50 metres in 1891 when the river was much more likely to flood. The conditions in 1934 are apparently similar today. So, an event such as the one in 1934 represents the worst known event for flooding in Melbourne. However further upstream the upper Yarra Reservoir was completed in 1957, initially for the purpose of preventing flooding downstream.

4. Rating of Flood Events

The probability of a flood level being equalled or exceeded in any 1-year period can be expressed as a percentage, the annual exceedance probability or AEP, or as an average recurrence interval, or ARI. As an example, take a flood level which can be expected to be equalled or exceeded on average once every 100 years. In this case, the ARI is 100 years and the AEP is 1%. It is important to note that an ARI of, say, 100 years does not mean that the event will only occur once every 100 years. In fact, for every year there is a 1% chance (a 1 in 100 chance) that the event will occur. The use of annual exceedance probability (AEP) to describe the chance of a rainfall amount is generally preferred as it conveys the probability or chance

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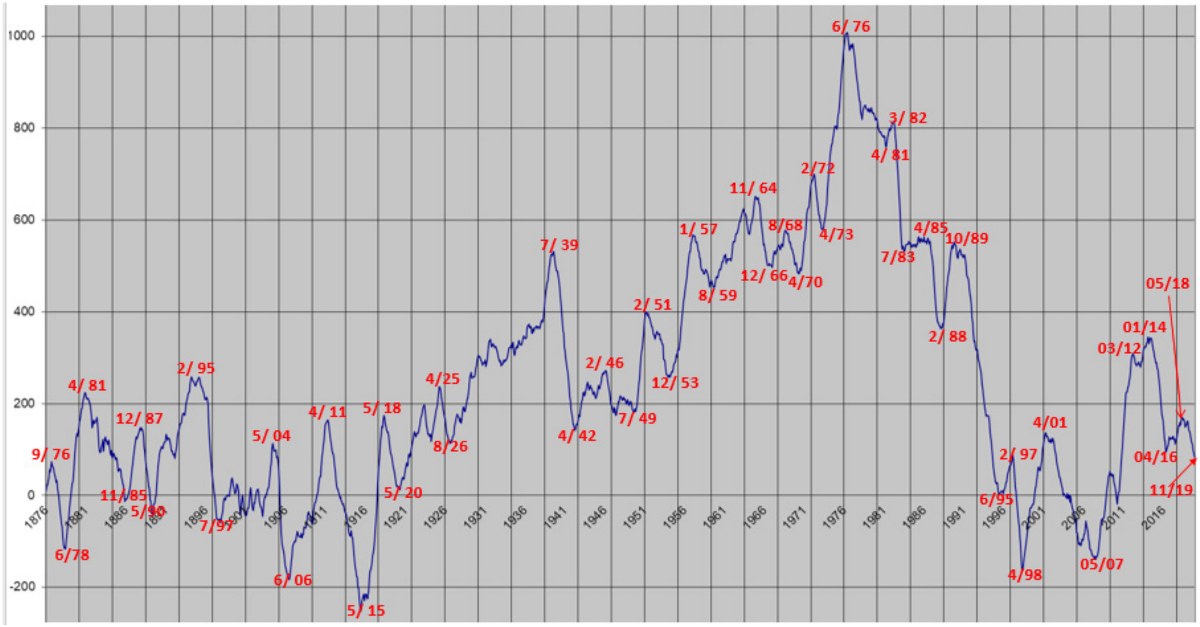

Figure 1a. Cumulative Southern Oscillation Index January 1876 to November 2019. Red numbers show the month and last two digits of the year.

that exists for each year. The alternative, ARI, is a term which is easily misunderstood however it is more widely used and appears to be favoured by the public, so we use it here as well as the AEP.

5. Climatology

For a summary of Victorian climate in general see the Bureau of Meteorology web site Climate of Victoria (weather-climate.com).

The cumulative Southern Oscillation Index (SOI) is shown in Figure 1. To generate this curve the monthly value of the SOI is continually added so for sustained positive values the curve rises and for negative values it falls. Events shown in the list are analysed using this cumulative SOI curve. Below rising (positive) SOIs are highlighted in red while falling (negative) values are blue.

Lists of event sequences during different phase of the SOI red is positive and blue is negative.

Jan 1876 to Sept 1876 zero events
Oct 1876 to June 1878 1 events
June 1878 to Apr 1881 4 events
Apr 1881 to Nov 1885 4 events
Nov 1885 to Dec 1887 4 events
Dec 1887 to May 1890 6 events
May 1890 to Feb 1895 9 events
Feb 1895 to July 1897 5 events
Aug 1897 to May 1904 10 events
Jun 1904 to Jun 1906 2 events
Jul 1906 to Apr 1911 16 events
May 1911 to May 1915 4 events
Jun 1915 to May 1918 8 events
Jun 1918 to Apr 1920 4 event
May 1920 to Apr 1925 9 events
Apr 1925 to Aug 1926 3 events
Sept 1926 to Jul 1939 41 events
July 1939 to Apr 1942 one event
May 1942 to Feb 1946 3 events
Mar 1946 to July 1949 6 events
Jul 1949 to Feb 1951 5 events
Mar 1951 to Dec 1953 11 events
Dec 1953 to Jan 1957 17 events
Feb 1957 to Aug 1959 2 events
Sept 1959 to Nov 1964 10 events
Dec 1964 to Nov 1966 2 event
Dec 1966 to Aug 1968 2 events
Sept 1968 to Mar 1970 4 events
Apr 1970 to Feb 1972 9 events
Mar 1972 to Apr 1973 2 Events
Apr 1973 to Jun 1976 13 events
July 1976 to Jan 1988 15 events 8 of these –ve IOD
July 1983 to Apr 1985 6 events
May 1985 to Jan 1988 8 events 3 of these –ve IOD
Feb 1988 to Oct 1989 5 events
Nov 1989 to May 1995 15 events 8 of these –ve IOD
June 1995 to Feb 1997 6 events
Mar 1997 to Apr 1998 zero events
May 1998 to Apr 2001 7 events
May 2001 to May 2007 5 events

May 2007 to Jan 2014 26 events
Feb 2014 to Apr 2016 2 events
May 2016 to May 2018 7 events
June 2018 to Dec 2018 1 event

From this between 1876 and 2019 there were 210 positive events and 109 negative events which clearly shows that heavy rain and flooding in Victoria are more likely in positive phases of the SOI. From July 1976 some events are highlighted which occurred during negative phases of the Indian Ocean Dipole (IOD) which is discussed below.

Interdecadal Pacific Oscillation and major events coinciding with major Global Temperature rises from 1915 to 1939

From [1] sustained positive SOI episodes occur during negative phases of the Interdecadal Pacific Oscillation (IPO) and they state that current understanding of the IPO doesn't enable a decision on whether pre 1976 Climate Shift sequences of numerous SOI positive episodes will resume.

Coinciding with strong Global temperature rises with only moderate Global Carbon emissions were a series of strongly positive SOI episodes where from May 1915 to July 1939 when the monthly average SOI was +2.7. From May 1915 to July 1939 there were 58 events during the positive phases of the SOI and 7 events during the negative phases. This period was also very active in other regions for example from June 1915 to July 1939 Nineteen Tropical Cyclones (16 of which occurred during positive phase of SOIs) impacted on the coast north of Brisbane. Of these the following major cyclones occurring during positive phases of the SOI, 1916 Whitsunday Severe tropical cyclone 62 lives lost in Clermont, 1918 Severe tropical cyclone Mackay 30 lives lost, 1918 Severe tropical cyclone Innisfail 77-97 lives lost; 1927 Severe tropical cyclone 47 lives lost and 1934 Severe tropical cyclone Port Douglas 79 lives lost. Over the same time there were 28 major impact events causing severe coastal damage between Brisbane and the Victorian Border (Callaghan 2019) and 26 of these occurred during positive phases of the SOI.

Despite these large sequences of devastating events occurring during sustained periods of positive SOIs this period has been classified as a positive phase of the IPO [4]. This does not seem to be logical considering other positive phases of the IPO. It would appear this classification of the IPO is in error or our understanding of the IPO is in error.

Negative IPO 1945-1976

This IPO produced 58 Victorian events when the monthly SOI was positive and 27 events with a negative SOI. Over the same time there were 70 major impact events causing severe coastal damage between Brisbane and the Victorian Border [5] and 45 of these occurred during positive phases of the SOI. This is what we have come to expect during negative phases of the IPO. From the late 1940s to the 1976 shift when the monthly SOI was averaging +2.5 the global temperatures fell as Global Carbon emissions began to increase dramatically (Figures 1b and 1c). This halted the earlier period of strong Global temperature rises from around 1910.

The 1976 Climate Shift and Victorian Heavy rainfall.

Note the marked change in the cumulative SOI in Figure 1 where the graph sharply turns from rising to falling in June 1976. This has been called the 1976 Climate Shift [6]. As the curve plummeted in Figure 1a following the Climate shift there was a marked change in Global climate producing high impact long lasting events all over the Globe. Severe Extra-Tropical cyclones lashed California, for example [7,8] there was extreme beach erosion in California in the 1982/1983 and the 1997/1998 El Niño events. There was a Massive rise in the Caspian Sea (see Figure 1d) in the 20 years followed the shift. Extensive beach erosion occurred in coastal Brazil (G Buden personal communication) over the twenty-year period following the Shift and in sub-tropical eastern Australia a long-term tropical cyclone hiatus began [10,11]. Rainfall was markedly reduced in New South Wales [12] in the 20 years following the shift. There was an unprecedented number of El Niño events following the Shift and five of these produced very dry conditions in Victoria, 1982-83,1997-98, 2002-03, 2006-07 and 2015-16. Three produced partly dry conditions in Victoria 1991/92, 1994-95 and 2009-10, and two had little effect on Victoria 1987-88 and 1993-94.

However, conditions recovered with a major strong La Niña event in 2010-12. The years 2010 and 2011 ranked third and second as the wettest calendar years for Australia, with 703 mm and 708 mm respectively, both well above the long-term average of 465 mm. Combined, the two events yielded Australia's wettest 24-month period on record. This contributed to the most active period in the Victoria record when from May 2007 to January 2014 where there were 26 events and from Figure 1a the graph was mostly rising (SOI positive) over this interval. The critical factor for Victorian heavy rainfall is whether sustained positive SOI episodes resume like those preceding the Climate Shift. Following the climate shift there were 57 positive events and 46 negative events which suggests a much weaker influence from the SOI. This occurred as

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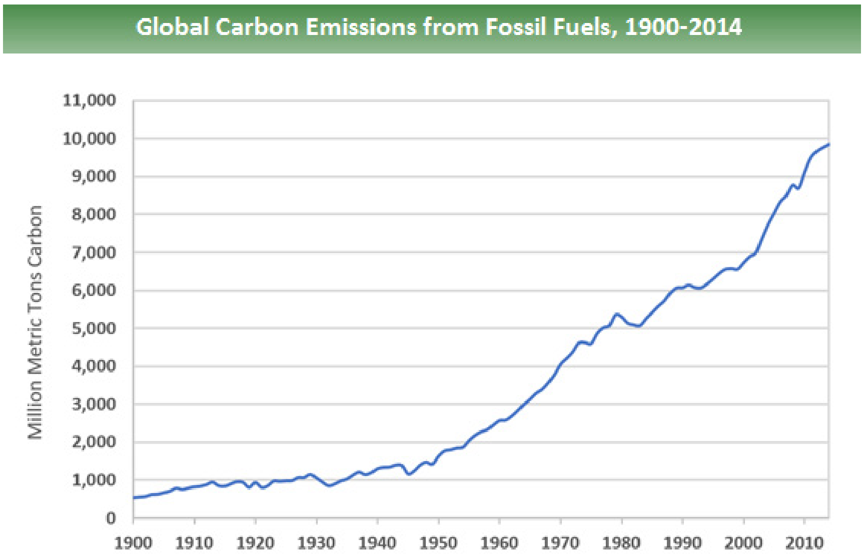

Figure 1b. Global, Regional and National Fossil-Fuel CO_2 Emissions [14]

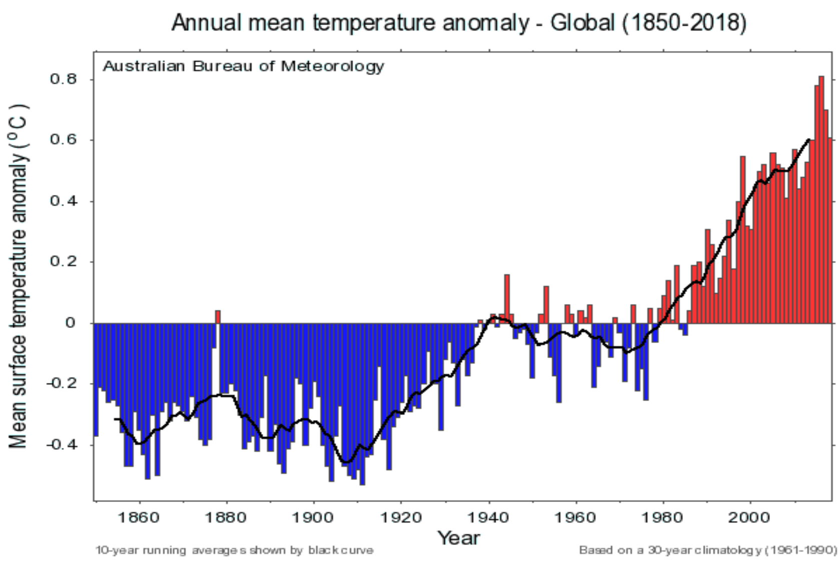

Figure 1c. Global annual mean temperature anomaly 1850-2018 with 10 year running average marked by bold black curve.

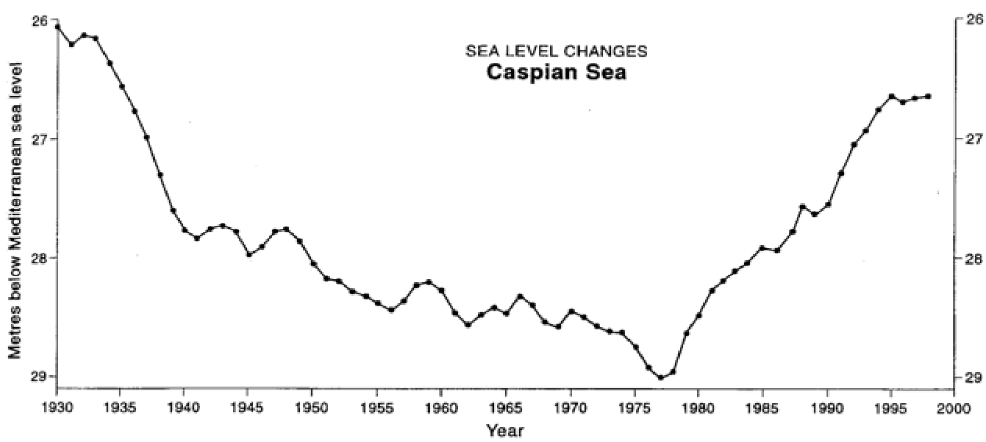

Figure 1d. Sea level rides Caspian Sea after Climate Shift from [9].

negative SOI episodes were more prevalent following the climate shift. From July 1949 to June 1976 the monthly average SOI was +2.5 and following the Climate Shift from July 1976 to April 1998 the monthly average SOI was -4.5. Overall, the Climate shift affected the number of Victorian events occurring. From May 1950 to the Shift they occurred at a rate of 2.7 events per year and after the shift at a rate of 2.3 events per year. The number of events post Shift was helped by the number of events generated by negative Indian Ocean Dipole (IOD) effects (see below) and a strong La Niña. Before and after the Climate shift there was a complex interaction with Global temperature tendencies and Global Carbon emissions. Following the Shift up to 2000 the strong Global temperature rises resumed, this time under strong carbon emission increases (see Figure 1b).

The number of Victorian flooding events with a negative SOI were increased after the shift under the influence from negative Indian Ocean Dipole (IOD) episodes.

IOD data is available at https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Data/dmi.long.data

Intensity of the IOD is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E and 10S-0N). This gradient is named as Dipole Mode Index (DMI). When the DMI is positive then, the phenomenon is referred as the positive IOD and when it is negative, it is referred as negative IOD which results in increased rainfall over Victoria. Of the 15 negative SOI events from July 1976 to June 1983, 8 occurred during negative IOD episodes. With the 23 negative SOI events from May 1985 to May 1995 again 11 occurred during negative IOD episodes. This is unusual as research has shown that the IOD events are generally not independent of ENSO variability [13]. Most positive IOD events tend to occur during El Niño events while negative IOD events dominate during La Niña [15]. Victoria experiences widespread rainfall and its wettest conditions when La Niña aligns with a negative IOD as happened during the spring and summer of 2010 - 2011 that ended the Millennium Drought [15,16]. Conversely, the driest condition prevails when a positive IOD co-occurs with El Niño. Hence, they act together either to significantly reduce or amplify rainfall over Victoria.

Droughts

Three prolonged periods of below-average rainfall occurred during the instrumental period [17]: The Federation Drought (1896 – 1905), the World War II Drought (1936 – 1945) and the Millennium Drought (1997 – 2009), each with different characteristics [17,18]. During these drought years heavy rain/flood events continued in Victoria. In the 1896 – 1905 drought there were 12 events in Victoria, during 1936 – 1945 there were 13 events and during 1997 – 2009 there were 16events. During these three drought these Victorian heavy rain events occurred at the rate of roughly one event per year against the long-term average of around 2 events per year. The three driest years since 1900 were 1967, 1982 and 2006. Over these three years only 1967 had an event occurring and this was on the 24-hour period ending 2300 UTC 29 June 1967 when an ECL dumped up to 148.6 mm in southwest Gippsland. So even in extremely dry years very heavy rainfall event can occur somewhere in Victoria.

Monthly Occurrences of strong Victorian impacts

The 319 events broken up into monthly occurrences were as follows with the 103 events following the Climate Shift in red:

January 26 (6); February 33 (5); March 26 (4); April 27 (9); May 16 (4); June 36 (12); July 22 (9); August 26 (9); September 27 (11); October 31 (12); November 19 (9); December 30 (13). The largest number occurred during June and these were dominated by ECLs events. Cool season months April to October numbered 185 while warm seasons had 134 events. There were also large numbers of events during October with less ECL event with more events occurring around the Northeast Alps. This would indicate that snow melt was playing a role during the October events. Large number of events also occurred in February and December where tropical interaction events dominated. Following the climate shift there were 66 cool season events and 37 warm season events.

The number of April to October events fell following the Shift from 0.94 events per year before the Shift and 0.64 events per year following the shift. In the active positive SOI burst of 26 events from May 2007 to January 2014 half occurred during April to October, that is at the rate of 1.6 cool season events per year. Therefore, these bursts of sustained positive SOI periods can produce large numbers of cool season events.

6. Examples of Synoptic Patterns Using Maximum Impact Events

28 November -1 December 1934 Intense low developed Bass Strait

This low (see Figure 2) rapidly intensified as it moved from west of King Island to a 982 hPa low just off the Gippsland Coast at 2300 UTC 29 November 1934 and then moved slowly towards the south southeast while

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weakening slowly. There was a tropical influence in this development with an extensive area of northerly winds flowing down to Victoria at 2300 UTC 27 November 1934. Then a tropical low developed over Southwest Queensland by 2300 UTC 28 December 1934 before interacting with the King Island low.

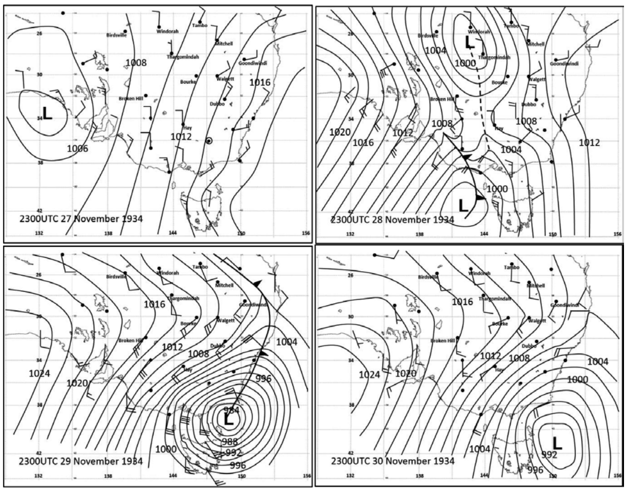

Figure 2. Mean sea level pressure distribution (hPa) with surface average wind observations (normal plotting convention) for 2300 UTC 27 November 1934 (top left), 2300 UTC 28 November 1934 (top right), 2300 UTC 29 November 1934 (lower left) and 2300 UTC 30 November 1934 (lower right)

Rainfall totals of 144 mm fell in Melbourne from 0900 UTC 29 November 1934 to 1630 UTC 30 November 1934. In the higher reaches of the Yarra River an average rainfall of 224.7 mm fell between 0700 UTC 29 November and 1100 UTC 1 December causing the Yarra River to rise to the record heights. In these upper regions east of Melbourne totals exceeded 350 mm within 48 hours. The top 24 hour rainfall totals were at Hazel Park 44 km south of Morwell with 266.7 mm and Sherbrooke 24 km north-northeast of Cranbourne 264.9 mm. At the Johnstone Street Bridge Collingwood around 1100 UTC Saturday 1 December the Yarra River was 39 ft. 7 in. (12.05 metres) above summer level the highest since 1891 when it reached 41 feet (12.50 metres) above summer level on Monday 13 July 1891.

There were very high ARIs associated with this event (Bunyip River ARI >150 years and ARI 100 years for the LaTrobe River, Yarra River and Yea Rivers. The SS Coramba sunk off Phillip Island and the crew of seventeen lives were lost. The severe overland flooding resulted in 20 people drowning. A party of fishermen from Lakes Entrance, with police, rowed for miles in swiftly flowing, debris-filled water in the Moe and Trafalgar districts, and saved many lives. Disastrous flooding was widespread over the Yarra Valley, South Gippsland, and the Latrobe River District, with major stock, crops and property losses. The damage was exacerbated by the gale force winds that accompanied the rain, causing heavy livestock losses through exposure, as well as much property damage. Very many trees were uprooted by the combination of high winds and sodden ground. Six thousand people were left homeless, and in Melbourne some 400 houses and factories were flooded. More than 2,500 people were rendered homeless at Mordialloc, Edithvale, Chelsea and Carrum.

February 2005 Low

This low (Figure 3 top left) intensified to 985 hPa as it moved south down into Gippsland by 1000 UTC 2 February 2005 with the centre to the east of Bairnsdale and a secondary low forming near Hogan Island where storm force winds were reported. A series of trough lines marked by wind changes were denoted by dashed lines however they were no temperature or moisture discontinuities across these features. Heavy rain had fallen in the Melbourne area with the highest reports over the previous 12 hours were east of the City with 63 mm at Ferny Creek and 52 mm at Scoresby. The heaviest 12-hour totals in the synoptic weather stations were over Gippsland with 84 mm at Mount Nowa Nowa, 83 mm at Mount Moornapa, 80 mm at Mount Baw Baw, 60 mm at Bairnsdale and 57 mm at Orbost. Gales were indicated at Aireys Inlet, Point Wilson and Fawkner Beacon (over the Northern Bay near Melbourne).

By 1600 UTC 2 February 2005 the northern low moved west to Mount Baw Baw (top right frame Figure 3) while the low near Hogan Island intensified with winds their reaching hurricane force. Gales extended further north to Laverton. Heaviest 6-hour rainfall was 80 mm Mount Baw Baw, 76 mm Ferny Creek, 63 mm Scoresby, and 50 mm at Rhyll on Phillip Island. The trough lines still showed no temperature or moisture discontinuities across them.

At 1900 UTC 2 February 2005 (lower left frame) the northern low was near Coldstream while the southern low weakened dramatically and gales had extended northwards to Tullamarine. The trough through the Bay gained more frontal characteristics with generally warmer and moister conditions in the south to southeasterly flow to its east. Then by 2200 UTC 2 February 2005 (lower frame) the front had largely passed through Melbourne and the rain stopped (Melbourne City rainfall ceased at 2100 UTC 2 February 2005). Heavy rain and gales continued west of the front but east of the front the pressure gradient and winds eased.

For information on terrain see www.bom.gov.au/australia/radar/info/vic_info.shtml#melbourne02

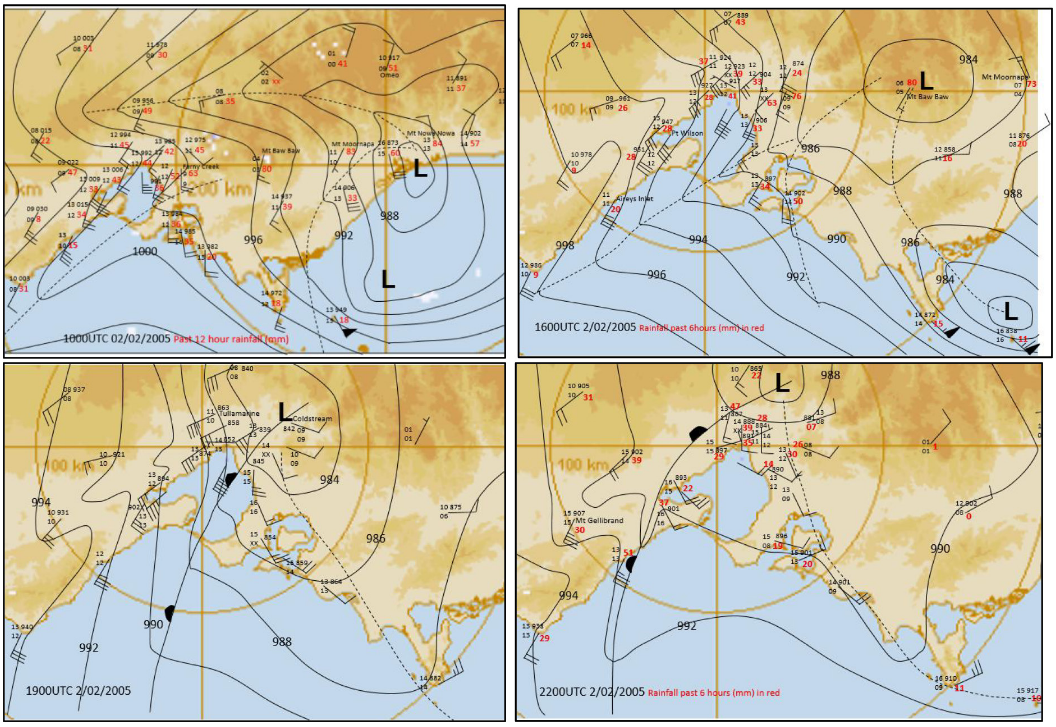

Figure 3. Mean sea level pressure distribution (hPa) with surface average wind observations for 1000 UTC 2 February 2005 (top left), 1600 UTC 2 February 2005 (top right), 1900 UTC 2 February 2005 (lower left) and 2200 UTC 2 February 2005 (lower right). Past rainfall totals are indicated in red.

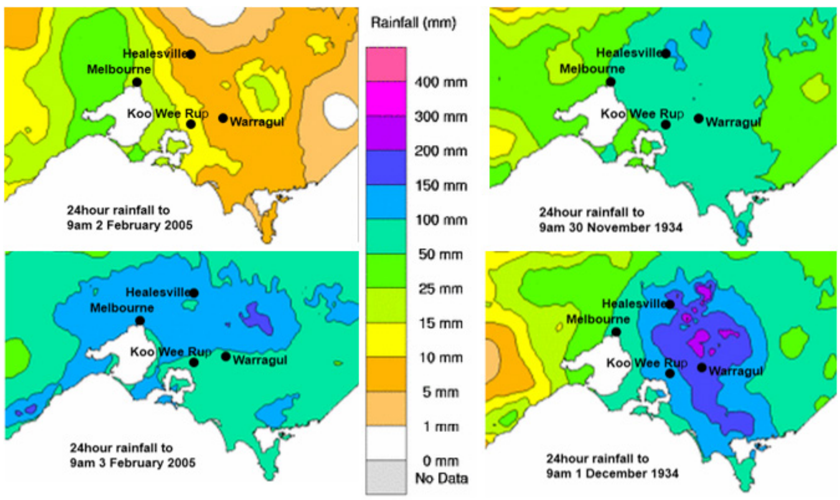

Figure 4. Twenty-four-hour rainfall (mm) to 2300 UTC 1 February 2005 (9 am 2nd local time and top left frame), 2300 UTC 30 November 1934 (9 am 31st local time and top right frame), 2300 UTC 2 February 2005 (9 am 3rd local time and lower left frame) and 2300 UTC 31 November 1934 (9 am 1st December local time and lower right frame).

Severe wind gusts caused extensive building damage in Melbourne and over 7,000 requests for assistance were received. Rainfall through the Melbourne area exceeded 100mm with an all-time 24-hour record for Melbourne CBD set at 120.2 mm (previous record 108 mm). Widespread riverine flooding occurred across the Port Phillip and Westernport Region. The damage from the low in New South Wales, Victoria and Tasmania reached $304 million 2011 AUD.

The Yarra River at Collingwood broke its banks for the first time since 1934. In Melbourne, major flooding was also experienced along the Dandenong and Kororoit Creeks. The Tanjil River at Tanjil Junction and Sunday Creek at Tallarook also experienced major flooding.

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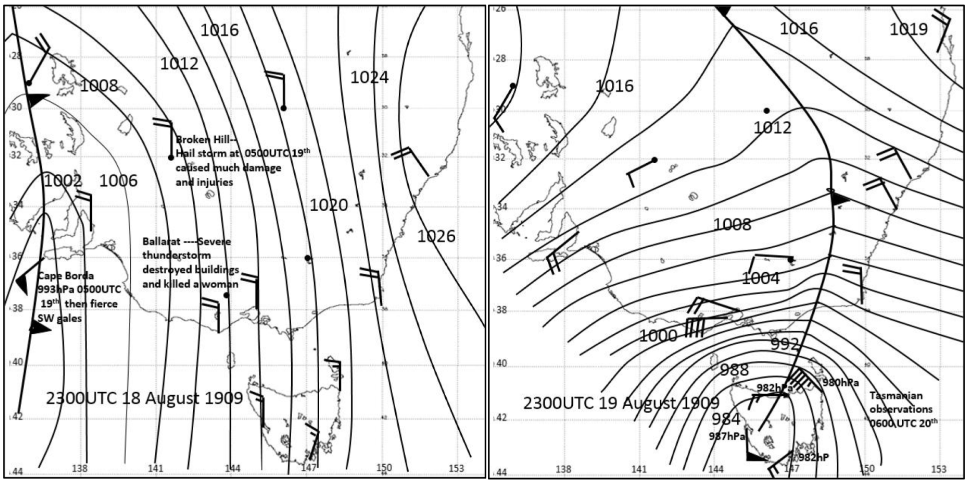

Figure 5. Mean sea level pressure distribution with surface average wind observations (normal plotting convention) for 2300 UTC 18 August 1909 (left) and, 2300 UTC 19 August 1909 (right).

Comparison of rainfall between the 1934 and 2005 events

Figure 4 details the rainfall distribution between the two events with the 2005 events moving west while the 1934 event moved slowly east. Consequently in 2005 the rain was concentrated more over the Melbourne area and to the west while in 1934 a band of extreme rainfall was focussed on a region from the Upper Yarra Valley (around Healesville) down to the south-southeast over South Gippsland.

19-20 August 1909 Western Districts

A 1000 hPa low south of Kangaroo Island moved towards southeast and intensified to below 985 hPa over SW Tasmania (see Figure 5). The mean sea level pattern before the rapid cyclogenesis (left panel) shows tropical northerly air flowing around the eastern flank of a developing low.

There were large major flood ARIs as follows- Loddon River Laanecoorie ARI 100 years, largest on record, Loddon River Bridgewater ARI 100 years, Loddon River Serpentine, Kerang & Charlton ARI 100 years. Major flood Yarrowee River Ballarat which was the highest flood levels on record.

There was a major flood Wimmera River at Horsham, Glenorchy, Dimboola and Jeparit 100 with ARI 100 years. There were 6 fatalities associated with this event.

The Laancoorie Weir on the Loddon River on Friday 20th gave way surging water down the river Valley and bridges were swept out of sight. The town of Bridgewater was almost inundated, and the inhabitants were rescued in boats brought from Bendigo. A storm swept over Ballarat. In a quarter of an hour there was loss of life; houses were levelled, and roofs carried away; chimneys collapsed; outbuildings and fences were whirled into the streets and home furnishings were saturated. A woman was killed by lightning and another was killed when a chimney collapsed on her. A man was drowned at Learmonth (NW of Ballarat) while crossing a creek when a flash flood came down the creek. Another man was drowned in the district from flash floods.

The heaviest 24 hour rainfall were at Daylesford, 35 km NE of Ballarat 29.2 mm 19th and 87.4 mm 20th, at Lyonville 39 km ENE of Ballarat 35.8 mm 19th and 100.1 mm 20th and at Avoca 23 km W of Maryborough, 30.2 mm 19th and 85.1 mm 20th.

To explain surface conditions in Victoria leading into the August rain, June was exceptionally wet, seeing in many places (e.g. Melbourne) a record number of rainy days for any month. The heavy June falls had already made the ground throughout Victoria very moist, and even though July rainfall was only above normal in the north of the State was of relatively little significance as evaporation was too low to dry the ground. There were heavy 24 hour falls in the Wimmera on 9 August 1909 (to 41.1 mm) and the third of four major depressions for the month arrived in western Victoria on the 17 August 1909. This produced very heavy falls upon already-saturated catchments on flat land where water was not draining away quickly. As the slow-moving depression linked with warm air from the Tasman Sea thunderstorms began to develop over the Wimmera region on the 18 August 1909.

West Coast of Victoria March 1946 heaviest rainfall in nearly 150 years.

A tropical low developed in southwest QLD by 2300 UTC 14 March 1946 (Figure 6) and interacted with a low

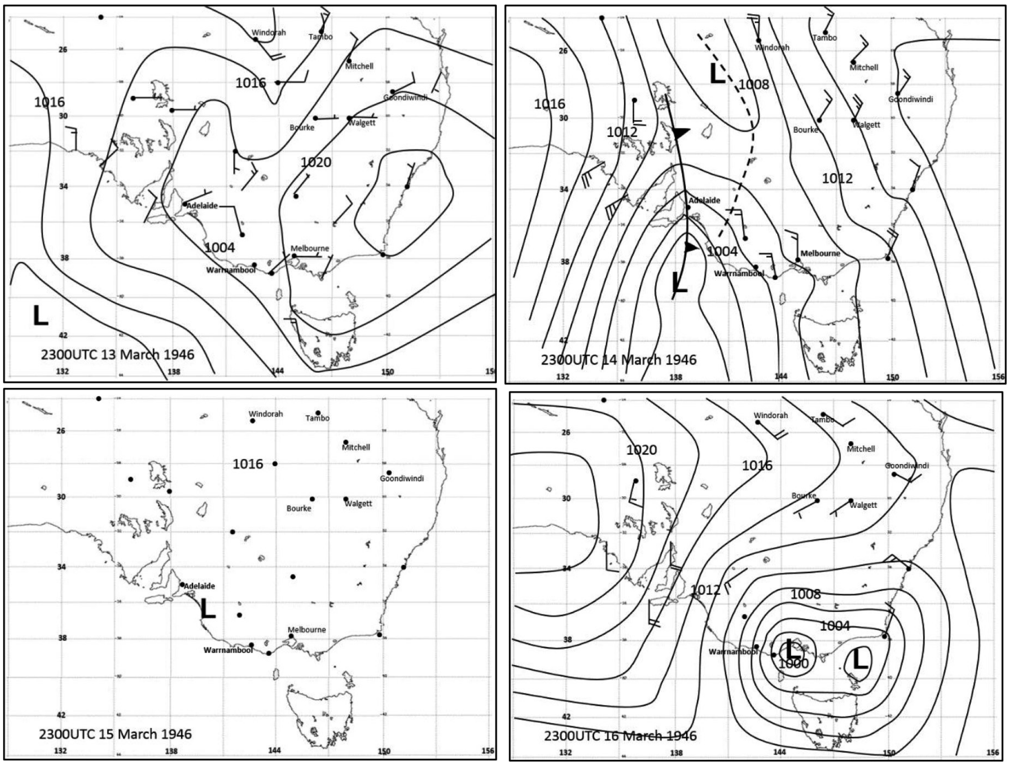

Figure 6. Mean sea level pressure distribution (hPa) surface average wind observations (normal plotting convention) for 2300 UTC 13 March 1946 (top left), 2300 UTC 14 March 1946 (top right), 2300 UTC 16 March 1946 (lower right) and for 2300 UTC 15 March 1946 (lower left) as there was no chart available just the position of the low.

near Mt Gambier to form a 998 hPa low near Melbourne on 2300 UTC 16 March 1946. From reports the heaviest rain (200 mm) fell in the Hamilton District from 2300 UTC 14 March 1946 to 0700 UTC 17 March 1946 while this interaction was underway. There were Seven Fatalities with major flooding in the Glenelg River at Casterton (ARI 100 years). Major damages occurred in all Western districts with various bridges washed away. The major flood in the Merri River at Warrnambool had an ARI greater than 100 years. The Moyne River at Port Fairy and Portland also had an ARI greater than 100 years. The floods which covered the western district and southern Wimmera from Natimuk to the sea and as far east as Mortlake. Scores of people were evacuated in Hamilton, Portland, Port Fairy, Warrnambool, Casterton, Heywood, Branxholme, Macarthur, and other towns.

Thousands of head of valuable stock perished. Scores of bridges were submerged or swept away, roads and railways washed out in many places, and telephone lines brought down.

•Record 24hour rainfall

Branxholme 77.0 mm 17^{th} 173.5 mm 18^{th} All-time record 1883 to present; Hawksdale 34.0 mm 16^{th} 158.2 mm 17^{th} record 1944 to 1995 42.2 mm 18^{th}; Koroit 45.2 mm 16^{th} 201.9 mm 17^{th} since 1889 record. Port Fairy 189.7 mm 17^{th} record since 1884.

Warrnambool 59.7 mm 16^{th} 167.1 mm 17^{th} record since 1867.

Yambuk -62.2 mm 16^{th} 181.9 mm 17^{th} record.

Recent Comparison Events to March 1946 in December 2008 and January 2011.

Two recent events are presented below to compare with the record 1946 event and in the next section the wind structures of these two events are presented. These structures are similar, but the heaviest rain was associated with the 2011 event where tropical air found its way right down to Victoria. This illustrates the probable structure of the 1946 event given it had a tropical inflow associated with it.

Low December 2008 (see Figure 7)

A 990 hPa low over Western Victoria intensified and formed a 983 hPa East Coast Low near Eden 13-14 Dec 2008. In this event the State Emergency Service, responded to more than 900 calls for help, mostly to remove fallen trees. Long term 24 h rainfall records for December were broken in Western Victoria on 13 December 2008 --Cavendish PO 65.0 mm 124 years of data; Nelson 69.4 mm 121 years; Merino 74.6 mm 117 years ; Branxholme

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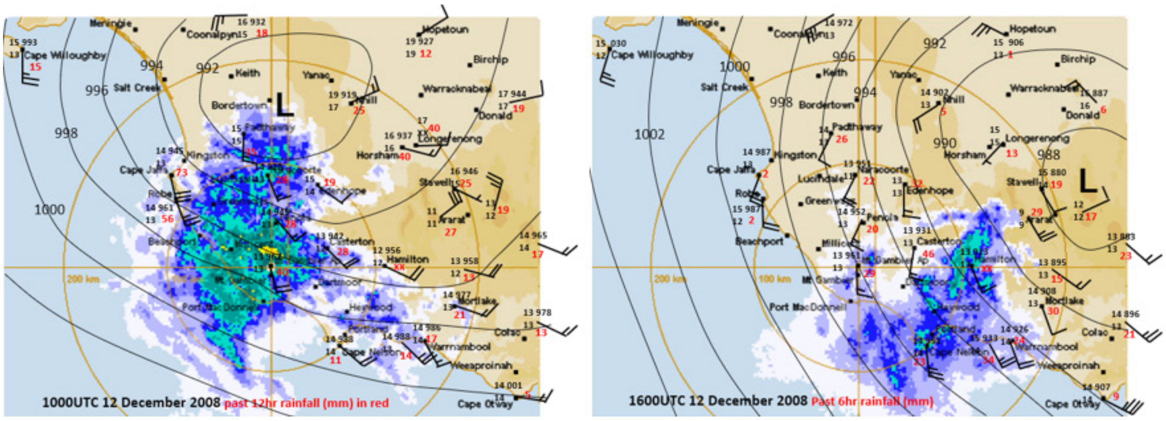

Figure 7. Mean sea level pressure distribution (hPa) during heaviest rainfall showing average wind plots, surface temperature and dew points in Celsius overlaid on Mt Gambier radar imagery with 100km range rings for 1000UTC 12 December 2008 (left with 12hour past rainfall in red) and 1600UTC 12 December 2008 (right with past 6-hour rainfall).

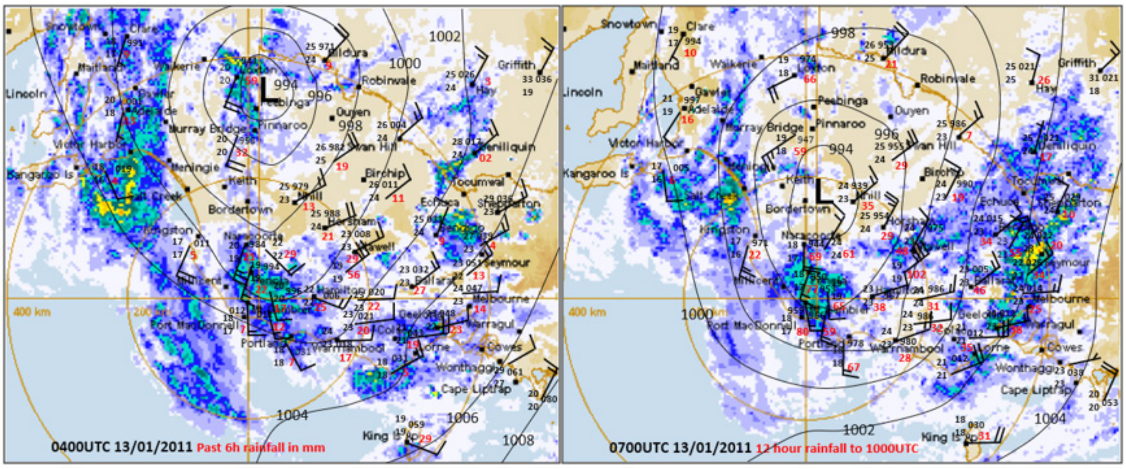

Figure 8. Mean sea level pressure distribution (hPa) during heaviest rainfall showing average wind plots, surface temperature and dew points in Celsius overlaid on Mt Gambier radar imagery with 200 km range rings for 0400 UTC 13 January 2011 (left with 6hour past rainfall in red) and 0700 UTC 13 January 2011 (right with past 12-hour rainfall).

87 mm 105 years; Penshurst 76.0 mm 72 years ; Casterton Showgrounds 86.0 mm 53 years; Strathdownie 85.5 13 47.2 1986 46years. Port Fairy 70.8 mm since 1898; 89.6 mm Benwerrin.

January 2011 Low with tropical inflow (see Figure 8)

11-12 January 2011 a 999hPa low developed near Portland moved SW on 13 January before intensifying to a 987 hPa low SW of Tasmania on 14 Jan 2011 with extraordinary tropical moisture advection down to VIC from the weather system causing the Brisbane Floods. A record flood peak hit the town of Rochester in Victoria. The Campaspe River near Rochester reached an historic peak of 9.12 metres - exceeding 1956 levels – and split the town in two. An evacuation warning was issued for Rochester's entire population of about 3,000 people. The major regional centres of Echuca, Kerang, Charlton and Horsham were also affected. The rainfall across the state between 9 am Thursday 13th and 9am Friday 14th was amongst the highest for the event and the most record breaking statewide. More than one-third of Victoria recorded rainfall totals in excess of 40 mm, which is approximately the equivalent of doubling the long-term average for January in this area. 25 stations recorded their highest ever daily rainfall for January during this 24-hour period, including the station at Maryborough which opened in 1878. 15 stations recorded rainfall totals in excess of 80 mm, with Mount William in the Grampians recording 132.8 mm and Nelson observing 113.2 mm.

In Figure 8 a 992 hPa low south west of Mildura at 0400 UTC moved down to south-western Victoria by 0700 UTC 13 January 2011. Moist tropical air (dewpoints well above 20 ^{0}C) was directed into Victoria around the

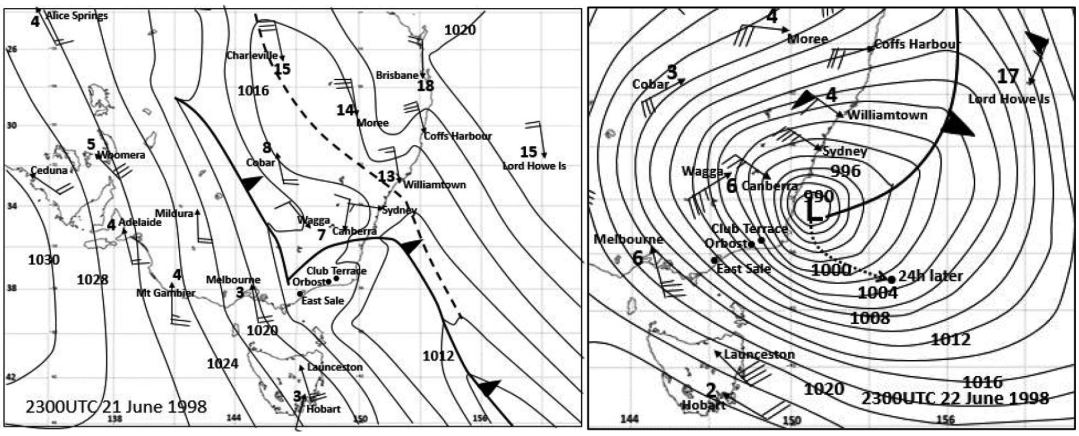

Figure 9. Mean sea level pressure distribution (hPa) showing gradient level winds (mostly at 900 metres elevation) and surface dewpoints for 2300 UTC 21 June 1998 (left) and for 2300 UTC 22 June 1998 (right).

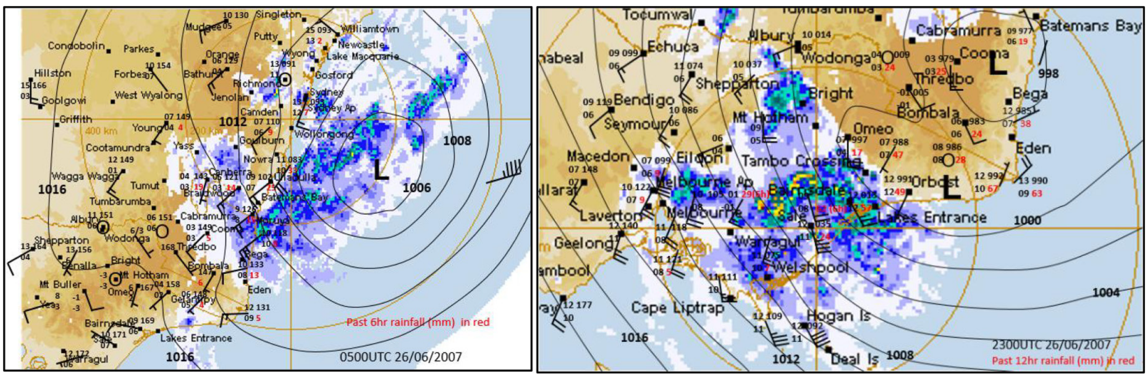

Figure 10. Mean sea level pressure distribution (hPa) during heaviest rainfall showing average wind plots, surface temperature and dew points in Celsius for 0500 UTC 26 June 2007 (left) and for 2300 UTC 26 June 2007 (right).

eastern side of the low. This covers a period of very heavy rainfall for example The Grampians (Mount William) recorded 102.0 mm in the 12 hours to 1000 UTC 13 January 2011. The Insurance Council of Australia damage statistic for this event was $(2011)126,495,000.

Gippsland ECLs 22-23 June 1998 (see Figure 9)

Extremely rapid development of an East Coast Low along the Far South Coasty of New South Wales.

In East Gippsland more than 1000 houses were flooded, at least 12 bridges were swept away. Club Terrace Post Office recorded 284.6 mm of rain in 24 hours, the heaviest daily total for rain ever officially recorded in East Gippsland. In Orbost 247.6 mm was recorded in the 24 hours to 9 am 24th June 1998 which was an all-time daily record since 1883.

The heaviest rain fell just after the sequence in the Figure above - In the head waters of the Mitchell River, which flows through between Sale and Orbost, 145 mm was recorded between 2300 UTC 22 June and 0500 UTC 23 June at both Crooked River and Waterford. In the Snowy River 220 mm was recorded at Basin Creek and 182 at Buchan between 2300 UTC 22 June and 1100 UTC 23 June 1998. In the Cann River Rockton in the headwaters recorded 125 mm also between 2300 UTC 22 June and 1100 UTC 23 June 1998.

Gippsland ECLs 26-27 June 2007 (see Figure 10)

The low in Figure 10 crossed the coast at Gabo Island (southeast tip of the Australian continent) around 1400 UTC 26 June 2007 - Gabo Island at 1100 UTC had and average wind of 230/29 knots and a bar of 1005 hPa. Then at 1700 UTC 040/23 knots 996.1 hPa with 58.0 mm in the 6 hr to 1700 UTC.The rain then developed over West Gippsland (see right frame Figure 10).

There were extreme rainfalls over eastern Victoria; Mt Wellington and Reeves Knob had 377 mm and 321 mm respectively.

•Mt Wellington recorded 319 mm of rain on the 28th June which is a Victorian state record for June and was the second highest in Victoria for any month. Another 9 stations with 25 or more years of record and 5 stations with

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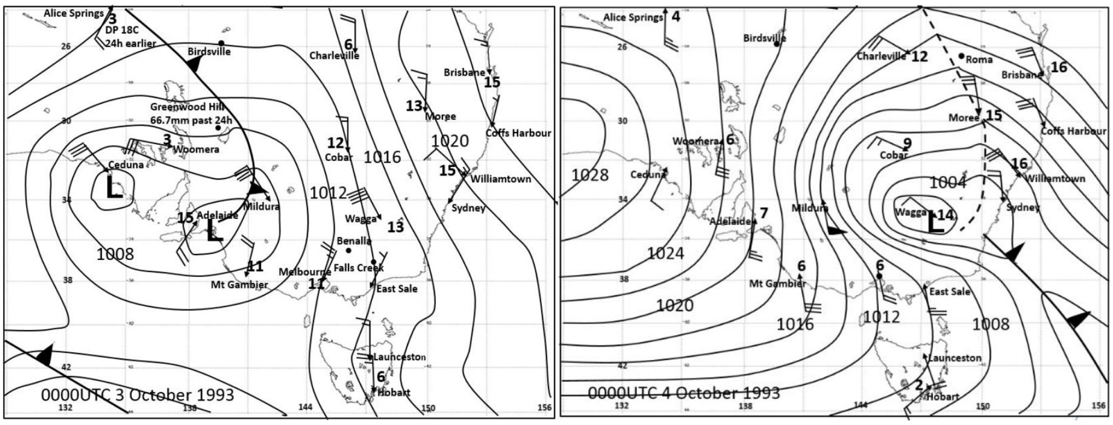

Figure 11. Mean sea level pressure distribution (hPa) showing gradient level winds (mostly at 600metres elevation) and surface dewpoints for 0000 UTC 3 October 1993 (left) and for 0000 UTC 4 October 1993 (right).

50 or more years of record set new records for the highest June daily rainfall. Most catchments in the Gippsland area were already saturated due to rain in the previous week. In West Gippsland the Traralgon creek catchment experienced major flooding.

•The Snowy river catchment experienced moderate to major flooding.

•Major Flood Macalister River Glenmaggie ARI 100 years Largest on record.

•Major Flood Thomson River Cowwarr ARI 25 years

•Major Flood Avon River The Channel ARI 40 years Stratford peaked around 8.9 metres.

•Major Flood Mitchell River Glenaladale peaked around 8.22 metres ARI 50years

•Major Flood Gippsland Lakes Entrance ARI 20 years

Victorian Alps October 1993 Low with tropical inflow (see Figure 11)

The extreme rainfall fell ahead of the cold front trough seen crossing Southeast Australia in Figure 11.

This occurred in a region of large-scale ascent as exemplified by the warm air advection wind profiles there as indicated by the Melbourne and Wagga upper winds as shown below. The pattern in the left frame is associated with heavy rain over Northern Victoria with air from the tropics flowing down to Victoria east of the low over South Australia.

Extreme rainfall on 3 - 4 October 1993 in catchments caused twelve mountain-fed rivers to flood on both the NE and SE sides of the Victorian Alps. Heavy damage occurred in NE Victoria where about 4,000 people were evacuated mainly at the towns and surrounding farms of Benalla (1,500+ evacuated), Shepparton, Myrtleford, Wangaratta and Euroa. Over 1000 people had to be temporarily housed in emergency centres. These figures are indicative of the large number of damaged homes and shops, some flooded by over a metre of water. The following are the larger ARIs experienced on some of the Victorian river systems affected:

Ovens at Bright and Myrtleford (1 in 100) and at Wangaratta (1 in 120); Broken River at Benalla (1 in 100); Broken Creek at Nathalia (1 in 100); Many roads and bridges were damaged, some destroyed. Thousands of kilometres of fencing were damaged. More than 3,500 sheep and 1,600 cattle died while crops, orchards and market gardens were destroyed, and huge dairy and other primary production losses resulted. There were also serious losses in Gippsland. The total estimated cost to Victoria was approximately $350 m. (One death was reported at Loxton, SA, due to downstream flooding on the Murray River). The heaviest 24hour rainfalls reported were: - Molyullah 14 km ESE of Benalla 189.0 mm 4th Edi Upper 234.4 mm 4th- Falls Creek 275.0 mm 5th -Mount Buffalo 212.0 mm 4th.

Overland flooding in Melbourne from extensive thunderstorms 2 December 2003 (Figure 12)

Overnight from the 2nd to the 3rd December 2003 severe thunderstorms formed near Craigieburn around midnight. Heavy rainfall was recorded in the northeast suburbs of Melbourne with the largest falls being 108 mm at Viewbank (Automatic Weather Station) 107 mm at Merri Creek Bell St, 106.6 mm at Eastern Golf Club, 104.6 mm at Banksia St Heidelberg, 99.8 mm at the Eastern Freeway, 88.4 mm at Gardiner Creek, 87 mm at Northcote and 78.2 mm at Lower Plenty. This rainfall caused flooding in many northeast suburbs and most of it occurred within a one to two-hour period around 1500 UTC 2 December 2003.

 DOI: https://doi.org/10.30564/jgr.v4i3.3204

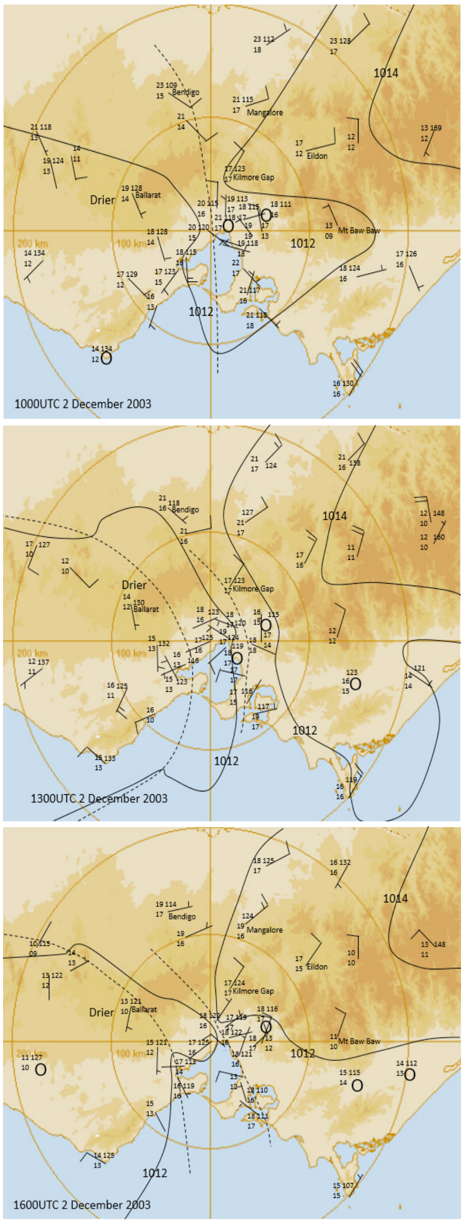

Figure 12. Mean sea level pressure distribution (hPa) showing average surface winds, surface temperatures and dewpoints for 1000 UTC 2 December 2003 (top left), 1300 UTC 2 December 2003 (top right) and for 1600 UTC 2 December 2003 (lower left).

At Viewbank Automatic Weather Station (AWS) 27.0 mm was recorded in 14 min to 1439 UTC 2 December 2003, 24.0 mm in 39 min to 1530 UTC and 76.2 mm was recorded between 1425 UTC and 1530 UTC 2 December 2003. Radio reports at the time suggested that the heaviest rain was in the Preston to Northcote area which is 8km west of Viewbank. The Melbourne CBD registered 32.2 mm in the 1 hour to 1430 UTC 2 December 2003. The hourly rainfall rates were consistent with an ARI 100-year event. Hail to 2.5 cm diameter was reported at Fairfield during the early morning.

Overland flooding in Melbourne from extensive thunderstorms 29 December 2016 (Figure 13) with strong tropical inflow

Figure 13 shows a trough (dashed line) south west of Melbourne with general northerly to northeasterly winds to its east. The stations displaying these winds have dewpoints of 22^{0}C to 24^{0}C (except for mountain stations) indicating their tropical origins.

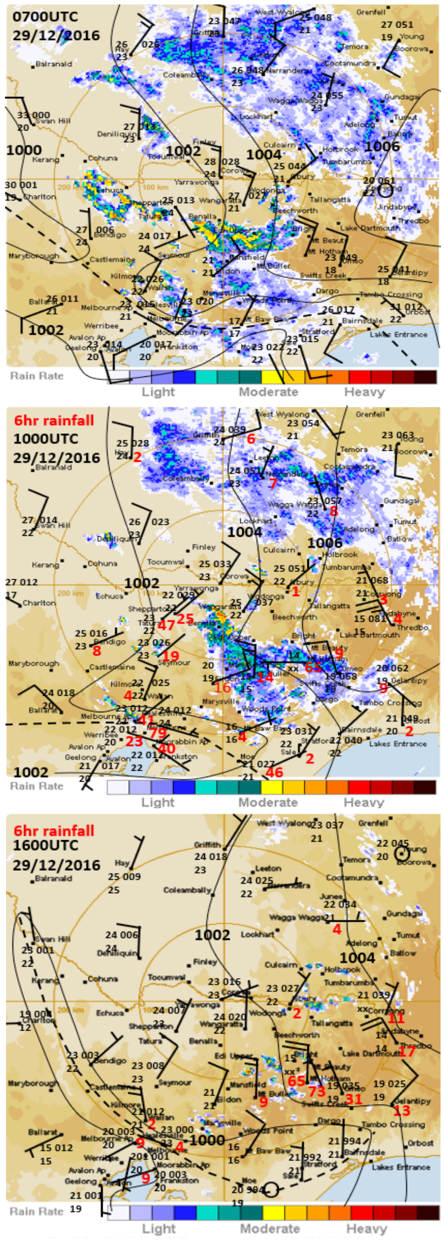

Figure 13. Mean sea level pressure distribution (hPa) showing average surface winds, surface temperatures and dewpoints overlaid on Yarrawonga radar with 100 km range rings for 0700 UTC 29 December 2016 (top left), 1000 UTC 29 December 2016 with past 6 hour rainfall (top right) and for 1600 UTC 29 December 2016 with past 6 hour rainfall (lower left).

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Severe thunderstorms moved from the NW across the whole Melbourne metro area during the afternoon peak. 40 to over 70 mm was recorded frequently in around 30 minutes producing widespread flash flooding. Roads and expressways rapidly became impassable, including the Western Ring Road and Tullamarine Freeway while rail services were delayed or suspended, and trams delayed by deep water. The highest short-duration rainfalls during this storm were at Viewbank, in the north-eastern suburbs of Melbourne, where 40.2 millimetres fell in 15 minutes between 3.07 and 3.22 p.m. 29/12/2016.This is amongst the heaviest known rainfalls for such a duration in Victoria (Table 2) This rainfall rate surpassed the 1% annual exceedance probability rainfall. Indicative of the tropical influence Melbourne equalled its highest dewpoint on record for any month. The December 2016 event had a slightly higher peak dewpoint (24.0 °C) than those recorded on 13 January 2011 (23.9 °C) or 4 February 2011 (23.2 °C), although the very high dewpoints were sustained over a longer period in the two 2011 events.

Overland flooding in Melbourne from extensive thunderstorms February 2011 A trough with tropical inflow (see Figure 14)

During 4-5 of February 2011 high levels of moisture associated with ex-Tropical Cyclones Yasi and Anthony fed into a slow-moving surface low pressure trough extended from central Australia, through NW VIC and Melbourne. The dotted line in Figure 14 shows the location of the trough and its movement towards Melbourne. Tropical air is indicated northeast of the trough lone by dewpoints reaching 24^0C to 25^0C.

Major floods many stream & widespread flash flooding resulted. The persistence of the trough provided conditions that allowed thunderstorms to develop one after the other, affecting large areas of Victoria (SES received in the order of 6000 requests for assistance). The south-eastern suburbs of Melbourne saw repeated thunderstorms, resulting in total rainfall in excess of 150 mm at some locations. Widespread flash-flooding was reported around the Metropolitan area. Numerous stations recorded their highest daily rainfall for February. The heavy rain fell on catchments already saturated by the December and January rain events leading to widespread riverine flooding. Major flood warnings were issued for the Bunyip River, Dandenong Creek and Sunday Creek. A mean sea level sequence in Figure 1 shows a trough through southwest Victoria with moist tropical air (dewpoints above 20^0C) flowing in from the north moved eastward through Melbourne. During the sequence in Figure 1 some of the heaviest rain was recorded in Melbourne

For example, Moorabbin recorded 48.2 mm in 1 hour to 0730 UTC 4 February 2011; 24.2 mm in 1 hour to 0900 UTC 4 February and 82.0 mm in 4 hours to 1000 UTC 4 February. The Insurance Council of Australia damage statistics for this event was \$(2011 AUD) 487,615,000.

March 2011 Un-Official 24 hr rainfall Event (see Figure 15)

This event was not considered a major flood event as the only major flooding was recorded in the Snowy River catchment, driven by rainfall in NSW. The extreme rainfall was much more isolated causing flash overland flooding.

This record was 377.8 mm at Tidal River (Elevation 15 metres) in the 24 hours to 2300 UTC 22 March 2011 and

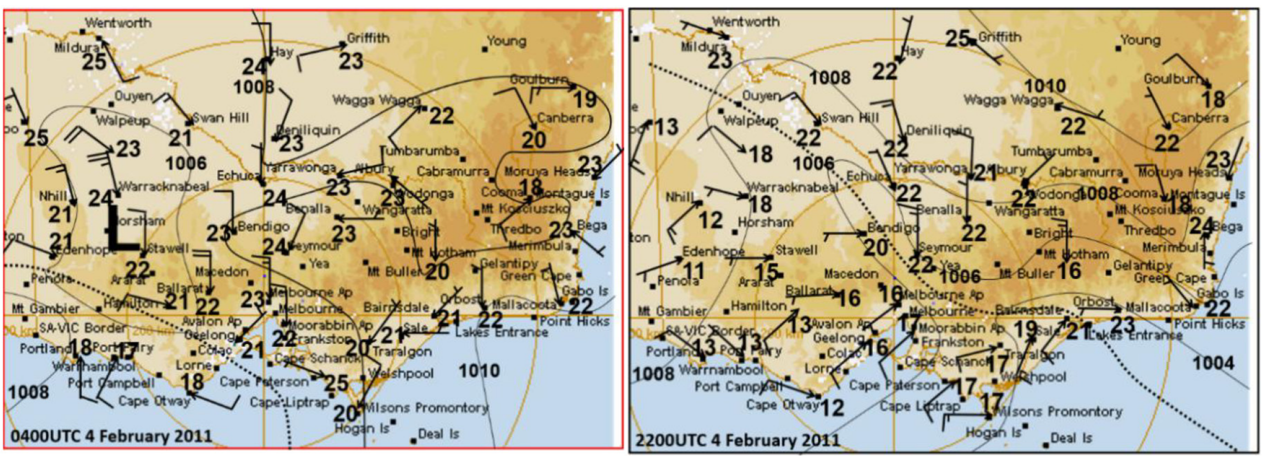

Figure 14. Mean sea level pressure distribution (hPa) with surface average wind observations (normal plotting convention) and dewpoints (degrees Celsius) dotted line marks trough position for 0400 UTC 4 February 2011(top left), 1100 UTC 4 February 2011 (top right) and 2200 UTC 4 February 2011 (lower left).

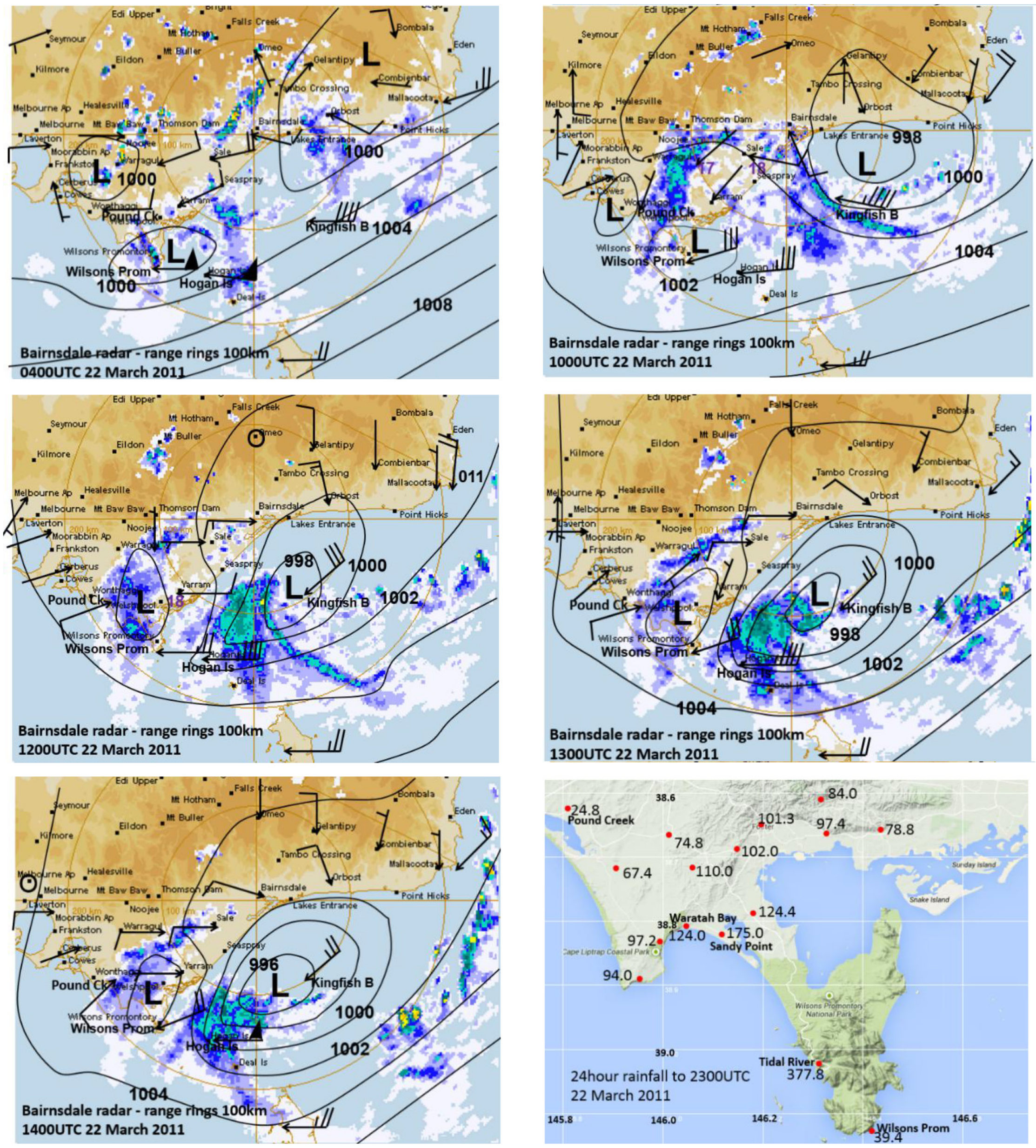

Figure 15. Mean sea level pressure distribution (hPa) together with average surface wind observations (normal plotting convention) overlaid on Bairnsdale radar images for 0400 UTC 22 March 2011(top left), 1000 UTC 22 March 2011(top right), 1200 UTC 22 March 2011 (centre left), 1300 UTC 22 March 2011 (centre right), 1400 UTC 22 March 2011 (lower left) and in the lower right frame the 24 h rainfall totals in the Wilsons Promontory region to 2300 UTC 22 March 2011.

this at the time was an un-official Bureau of Meteorology rain gauge. The is not generally a heavy rainfall site as the second highest daily total listed is 122.2 mm in 24 hours to 2300 UTC 27th August 1973 which was another isolated heavy fall observation associated with an ECL and not included in current list of events.

The heaviest rainfall from radar began at Tidal River about 0800UTC 22 March and was gone by 1700 UTC 22 March. Pound Creek and Wilsons Promontory Automatic Weather Stations received much lighter rainfall over the 24 hours 24.8 mm and 39.4 mm respectively. From the MSL sequence below in Figure 15 the main low near Kingfish B had heavy rain associated with it but this remained over water. The secondary low which formed near Pound Creek then became anchored between Pound Creek and Wilsons Promontory with all the heavy rain between those two stations. In the lower right frame, the rainfall distribution shows the largest rainfall reports in that area. During the heavy rainfall the dewpoint at Wilsons Promontory was 18 degrees Celsius indicating a relatively

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warm moist environment.

The rainfall occurred in an area where NCEP/NCAR reanalyses indicated there was large scale warm air advection at low to middle levels. The reanalyses however did not resolve the complex mesoscale lows in Bass Strait near Wilsons Promontory.

7. Examples of Turning Winds with Height during Major Events

There is limited radiosonde coverage in the heavy rainfall areas of Victoria in the Northeast and in recent years in Gippsland, however there is sufficient data available for some of the big impact events shown below to suggest a strong relationship between anticyclonic turning of the winds and extreme rainfall as shown for many parts of the globe. This investigation adds to a series of papers which related the turning of the winds anticyclonically with height in the lower to middle troposphere with extreme rainfall [19-25].

See examples below:

April 1977

Flash Flooding and Victorian Rainfall Records as follows at Laverton rain commenced around 0515 UTC 7 Apr 1977 and following recorded 137 mm in 3 h 137 mm at 153 mm in 4 h; In Northern Melbourne suburbs at Wollert 7 Apr 1977 191 mm in 12h; Mt Ridley 7 Apr 1977 193 mm in 12 h 192 mm and in the Southeast at Bentleigh East 7 Apr 1977 203 mm in 12 h.

Laverton winds 1700 UTC 6 April 1977 850 hPa 135/6.18 m/s; 700 hPa 020/10.30 m/s; 500 hPa 335/29.86 m/s.

Laverton winds 2300 UTC 6 April 1977 914 metres 135/18.02 m/s; 2133 metres 100/12.36 m/s; 3657 metres 095/7.2 m/s; 5486 metres 19.56 m/s.

Laverton winds 2300 UTC 7 April 1977 850 hPa 190/18.53 m/s; 700 hPa 185/19.56 m/s; 500 hPa 175/25.74 m/s.

March 1983

There were no major floods as the event followed a long drought period. Tanybryn (elevation 402 metres) in the 24 hours to 2300 UTC 21 Mar 1983 recorded 375.0 mm of rain (a record). This occurred as a large tropical low caused widespread heavy rain through Victoria with Madalya in West Gippsland recording 239.0 mm in the 24 hours to 2300 UTC 21 March 1983 which was a record (data from 1900). The record rainfall period was characterised by strong southeasterly flow onto the Otway ranges as a deep tropical low moved from near Cobar to the Melbourne area. From the surrounding radiosonde data shown below these strong southeast winds had the wind structure above the surface conducive to extreme rainfall where the winds turned anticlockwise with height between the 850 hPa and 500 hPa levels.

March 1983 Mount Gambier observations

At 0500 UTC 21 March 1983- 850 hPa 135/20.59 m/s; 700 hPa 125/18.53 m/s; 500 hPa 095/10.30 m/s.

At 1100 UTC 21 March 1983- 850 hPa.140/28.83 m/s; 700 hPa 100/16.47 m/s; 500 hPa 075/15.44 m/s.

At 1700 UTC 21 March 1983- 850 hPa 150/29.86 m/s; 700 hPa 110/8.24 m/s; 595 hPa 105/11.33 m/s.

Launceston observations

At 2300cUTC 20 March 1983- 850 hPa 085/6.18 m/s; 700 hPa 050/7.21 m/s; 650 hPa 030/9.27 m/s.

At 0500c UTC 21 March 1983- 850 hPa 115/8.24 m/s; 700 hPa 100/11.33 m/s; 595 hPa 065/16.47 m/s.

At 1100c UTC 21 March 1983- 850 hPa 095/16.47 m/s; 700 hPa 055/13.38 m/s; 500 hPa 350/9.26 m/s.

At 1700c UTC 21 March 1983- 850 hPa 105/21.62 m/s; 700 hPa 050/19.56 m/s; 600 hPa 045/19.56 m/s

Melbourne Observations: -

At 2300 UTC 20 March 1983- 850 hPa 110/27.8 m/s; 700 hPa 075/15.44 m/s; 500 hPa 025/13.38 m/s.

At 1100 UTC 21 March 1983- 850 hPa 075/15.44 m/s; 700 hPa 055/16.47 m/s.

February 2005 (Synoptic pattern in Figure 4)

The Melbourne Airport upper winds during the heaviest record rainfall turned anti-cyclonic with height indicating extreme rainfall as follows.

At 1100 UTC 2 February 2005 850 hPa 190/24 m/s; 700 hPa 175/24 m/s; 500 hPa 120/20 m/s; and at Melbourne Airport 1700 UTC 2 February winds; 850 hPa 205/27.28 m/s; 700 hPa 145/24.2 m/s 630 hPa 140/31.9 m/s.

Melbourne Airport rainfall was 52.0 mm 1000 UTC to 1600 UTC 2 February 2005 and 57.4 mm 1600 UTC to 2200 UTC 2 February 2005 then heavy rain ceased as backing of the winds became confined to below 850 hPa.

April 2004

Record 24hr rainfall West Gippsland including East Sale 108.8 mm in 24 hr to 2300 UTC 23 April 2004.

East Sale 1100 UTC 23 April 2004 850 hPa 165/4.63 m/s 700 hPa 120/5.15 m/s 500 hPa 070/15.44 m/s.

East Sale 1700 UTC 23 April 2004 850 hPa 185/26.25 m/s 700 hPa 160/20.59 m/s 500 hPa 160/22.65 m/s 400 hPa 155/19.05 m/s.

East Sale 2300UTC 23 April 2004 850 hPa 185/19.56 m/s 700 hPa 175/14.41 m/s 500 hPa 170/19.05 m/s.

Low December 2008 (Synoptic pattern in Figure 7)

In this event the State Emergency Service, responded to more than 900 calls for help, mostly to remove fallen trees.

Long term 24 h rainfall records for December were broken in Western Victoria on 13 December 2008 --Cavendish PO 65.0 mm 124 years of data; Nelson 69.4 mm 121 years; Merino 74.6 mm 117 years; Branxholme 87 mm 105 years; Penshurst 76.0 mm 72 years ; Casterton Showgrounds 86.0 mm 53 years; Strathdownie 85.5 13 47.2 1986 46 years. Port Fairy 70.8 mm since 1898.

Mount Gambier radiosondes 2300 UTC 11 December 2008 850 hPa 035/9.3 m/s 700 hPa 010/6.2 m/s 500 hPa 355/16.5 m/s.

Mount Gambier radiosondes 0400 UTC 12 December 2008 850 hPa 070/7.7 m/s 700 hPa 345/12.4 m/s 500 hPa 305/23.2 m/s.

11-13 January 2011 (Synoptic pattern in Figure 8)

The sounding at Melbourne at 0500 UTC 13 January 2011 showed the warm air advection type structure as follows 914 hPa 045/13.4 m/s; 850 hPa 025/21.1 m/s; 700hPa 025/18.5 m/s; 500 hPa 360/19.1 m/s; 400 hPa 345/22.7 m/s; and again at 1100 UTC 13 January as follows:

925 hPa 025/25.7 m/s; 850 hPa 15/32.4 m/s; 700 hPa 345/17.5 m/s; 500 hPa 335/20.6 m/s; 400 hPa 325/22.1 m/s.

The sounding at Mt Gambier at 2300 UTC 12 January 2011 also had this structure: - 925 hPa 055/5.7 m/s; 850 hPa 060/2.6/ m/s; 700 hPa 030/5.7 m/s; 500 hPa 350/27.8 m/s;0 400 hPa 345/29.9 m/s.

Gippsland September 1993

Major Flood Gippsland to ARI 70 years. Major Flood Maribyrnong River 53homes flooded.

Gippsland 24 hr rainfall_Madalya 149.4 mm 15th 105.0 mm 16th

24 hour rainfall near Maribyrnong catchment Heskett 94.2 mm 15th 52.2 mm 16^{th--}

Laverton 2300 UTC 13 September 1993 600 metres 165/7.2 1m/s; 900 metres 155/10.30 m/s; 2100 metres 130/12.36 m/s; 3600 metres 085/10.30 m/s; 4200 metres 045/10.30 m/s; 9000 metres 130/12.6 m/s.

Laverton 1700 UTC 14 September 1993 600 metres 175/17.5 m/s; 900 metres 175/17.5 m/s; 2100 metres 165/17.5 m/s; 3600 metres 160/16.47 m/s; 4200 metres 155/16.47 m/s.

Laverton 0500 UTC 15 September 1993 600 metres 180/16.47 m/s; 900 metres 170/17.5 m/s; 2100 metres 165/14.41 m/s; 3600 metres 160/13.38 m/s; 4200 metres 150/12.36 m/s.

East Sale 1700 UTC 15 September 1893 600 metres 200/15.44 m/s; 900metres 190/15.44 m/s; 210 metres 190/12.36 m/s; 3600 metres 175/12.36 m/s 4200 metres 165/15.44 m/s.

Gippsland June 1998 (Synoptic pattern in Figure 9)

Record floods Gippsland and in Orbost 247.6 mm was recorded in the 24 hours to 9 am 24th June 1998 (record).

Laverton (Melbourne) upper winds - At 1100UTC 22 June 1998 850 hPa 135/13.90 m/s; 700 hPa 120/6.69 m/s; 500 hPa 105/4.12 m/s.

At 2300 UTC 22 June 1998 850 hPa 155/18.53 m/s; 700 hPa 160/15.96 m/s; 500 hPa 080/8.24 m/s; At 1100 UTC 23 June 1998 850 hPa 195.00 15.44 m/s; 700 hPa 185/19.56 m/s; 500 hPa 175/8.24 m/s.

East Sale at 0500 UTC 23 June 1998 850 hPa 180/23.5 m/s; 750 hPa 160/20.0 m/s.

Gippsland June 2007 (Synoptic pattern in Figure 10)

Major Flood Macalister River Glenmaggie ARI 100 years Largest on record.

No more East Sale winds available but Melbourne showed the anticyclonic wind turning early. Melbourne 2300 UTC 26 June 2007 850 hPa 175/25.23 m/s 700 hPa 155/26.25 m/s 500 hPa 145/22.14 m/s.

Victorian Alps October 1993 (Synoptic pattern in Figure 11)

The following are the larger ARIs experienced on some of the Victorian river systems affected:

Ovens at Bright and Myrtleford (1 in 100) and at Wangaratta (1 in 120); Broken River at Benalla (1 in 100); Broken Creek at Nathalia (1 in 100);

The extreme rainfall fell ahead of the cold front trough seen crossing Southeast Australia in Figure 5.

This occurred in a region of large-scale ascent as exemplified by the warm air advection wind profiles there as indicated by the Melbourne and Wagga upper winds as shown below.

The heaviest 24 hour rainfalls reported were: - Molyullah 14 km ESE of Benalla 189.0 mm 4th Edi Upper 234.4 mm 4th- Falls Creek 275.0 mm 5th -Mount Buffalo 212.0 mm 4th.

Upper winds at Laverton (Melbourne) at 2300 UTC 2

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October 1993- 850hPa 355/8.24 m/s; 700 hPa 340/17.50 m/s; 320/24.71 m/s.

Upper winds at East Sale at 0500 UTC 3 October 1993- 600 m elevation 045/4.12 m/s; 900 m elevation 015/5.15 m/s; 1800 m elevation 290/11.33 m/s; 3600 m elevation 280/19.56 m/s; 4200 m elevation 275/22.6 m/s.

Upper winds at Wagga 0500 UTC 3 October 1993- 600mm elevation 340/17.50 m/s; 1200 m elevation 325/18.5 m/s; 3600 m elevation 330/23.68 m/s; 9900 m elevation 305/35.01 m/s.

Upper winds at Wagga at 1100 UTC 3 October 850 hPa 330/13.38 m/s;700 hPa 320/14.41 m/s; 500 hPa 300/17.50 m/s.

Upper winds at Wagga at 1700 UTC 3 October 1993- 1200 m elevation 005/12.36 m/s; 2100 m elevation 345/12.36 m/s; 3600 m elevation 325/14.41 m/s

Melbourne widespread thunderstorm flash flood events 6-7 April 1977

Low developed VIC on Front Flash Flooding and Victorian Rainfall Records

Intense rainfall Laverton 7 Apr 1977 from 0515 UTC 7 April 1977 3:15 pm 137 mm in 3 hours; Wollert 7 Apr 1977 in 12 hours recorded 191 mm -Mt Ridley 7 Apr 1977 in 12h recorded 192 mm; Bentleigh East 7 Apr 1977 in 12 h recorded 203 mm.

24 h totals to 9 am 8 April 1977 CENTRAL – Laverton 188.0 mm, Epping 129.0 mm; Essendon 100.0 mm; Greenvale 118.6 mm; Glenroy 102.0 mm; Healesville 101.0 mm; Kinglake 136.8 mm; Kallista 109.2 mm; Hurstbridge 104.0 mm; Melbourne Ap 132.4 mm; Maroondah Weir 111.0 mm; Powelltown 129.8 mm Mickleham 190.0mm; Mt Dandenong 107.4 mm; Sherbrooke 111.8 mm; Warburton 111.0 mm; Whittlesea 114.8 mm; Woori Yallock 121.0 mm; Yan Yean 143.0 mm;

17 houses unroofed and trees brought down in Altona. 50 houses evacuated when Merri creek flooded.

Laverton upper winds 1700 UTC 6 April 1977 – 850 hPa 135/6.18 m/s; 700 hPa 020/10.30 m/s; 500 hPa 335/29.86 m/s.

Laverton upper winds 2300 UTC 6 April 1977 – 914 metres 135/18.02 m/s; 2133 metres 100/12.36 m/s; 3657 metres 095/7.2 m/s; 5486 metres 345/19.56 m/s.

Laverton upper winds 2300 UTC 7 April 1977 –850 hPa 190/18.53 m/s; 700 hPa 185/19.56 m/s; 500 hPa 175/25.74 m/s.

December 2003 (Synoptic pattern in figure 12)

ARI 100 year flash flood event At Viewbank Automatic Weather Station (AWS) 27.0 mm was recorded in 14 min to 1439 UTC, 24.0 mm in 39 min to 1530 UTC and 76.2 mm was recorded between1425 UTC and 1530 UTC.

Melbourne upper winds 1100 UTC 2 December 2003

925 hPa 010/7.21 m/s; 850 hPa 010/6.18 m/s 700 hPa 310/8.24 m/s 500 hPa 275/13.90 m/s.

Melbourne upper winds 1700 UTC 2 December 2003

December 2016 (Synoptic pattern in Figure 13)

Special Climate Statement 59— The highest short-duration rainfalls during this storm were at Viewbank, in the north-eastern suburbs of Melbourne, where 40.2 millimetres fell in 15 minutes between 3.07 and 3.22 p.m. 29/12/2017.This is amongst the heaviest known rainfalls for such a duration in Victoria (Table 2) This rainfall rate surpassed the 1% annual exceedance probability rainfall (AEP)4 at all durations from 6 minutes to 6 hours, highlighting the very extreme nature of the rainfall

Melbourne equalled its highest dewpoint on record for any month, and December dewpoint records were set over many parts of Victoria, northern Tasmania, southern and western border areas of New South Wales, and the southern Northern Territory. In total, 21 long-term stations set December dewpoint records, with five of these setting records for any month. In Melbourne, the most immediately comparable events to the December 2016 event were those of January and February 2011. The December 2016 event had a slightly higher peak dewpoint (24.0 °C) than those recorded on 13 January 2011 (23.9 °C) or 4 February 2011 (23.2 °C)

Melbourne winds 2300 UTC 28 December 2016 925 hPa 340/15.4 m/s 850 hPa 310/12.3 m/s 700 hPa 300/13.90 m/s 500 hPa 300/14.93 m/s

4-5 February 2011(Synoptic pattern in Figure 14)

Around this time at 1100 UTC 4 February the routine radiosonde sounding at Melbourne showed a wind turning anticlockwise with height profile up to 700 hPa as follows: - 925 hPa 315/19.1 m/s; 850 hPa 310/16.0 m/s; 700 hPa 275/6.2 m/s. Further up to the northwest the heaviest rain at Mildura fell with 105.0 mm in 3 hours to 0700 UTC 4 February and the routine sounding at that station prior to this at 2300UTC 3 February showed the winds turning anti-cyclonically between 850 hPa 320/13.4 m/s and 500 hPa 300/10.3 m/s.

8. Mechanisms

The interaction of tropical air from the north and interacting with mid latitude weather systems approaching Victoria from the west is an important process in producing events with heavy rainfall over Victoria. In these systems wind structures can evolve which have flow patterns where the wind directions turn in an anticyclonic fashion from low up to mid-levels of the troposphere. Large scale ascent results from this wind structure aiding the development of rain and thunderstorms. This wind structure is particularly potent when there is cooler air aloft associated with it producing low static stability and extreme short-term rainfall can result. Low pressure systems along the east coast of Australia when they move closer to Victoria can produce the above wind structure over Eastern Victoria generating flood rains. This type of heavy rain system can also evolve from low pressure systems moving in from the west when there is tropical inflow of moist air on their eastern side.

9. Conclusions

Major flood and heavy rainfall events in Victoria which occurred since 1876 have been documented and these events were shown to have happened preferentially during positive phases of the Southern Oscillation (SOI). The synoptic weather patterns were analyzed and of the 319 events studied, 121 events were found to be East Coast Lows (ECLs) and 82 were other types of low-pressure systems. Tropical influences also played a large role with 105 events being associated with tropical air advection down to Victoria into weather systems. Examples were presented of all the major synoptic patterns identified. The 1976 Climate Shift and its influence on significant Victorian rainfall events were studied showing less periods of sustained monthly values of positive SOIs following the shift. It also showed increased occurrences of negative SOI events associated with the negative phases of the Indian Ocean Dipole following the shift. Despite this, one of the most active periods in Victoria's 144 years of heavy rainfall occurred after the Shift from 2007 to 2014 during a sustained period of positive SOIs so it remains to be seen if these extended positive phases continue in a similar fashion as occurred before the Climate Shift. It was shown how major Global Temperature rises were somehow related to this Climate Shift and needs to be understood more fully. A major period of Global warming occurred from 1915 to 1939 without obvious CO_2 emissions and positive SOI severe weather events dominated over this period even though Interdecadal Pacific Oscillation (IPO) data indicated a positive episode was operating and positive SOI events should have been far less prevalent. The cool season months of June and October were the months which had the largest event occurrences, June from ECLs and October with events affecting the Victorian Alps suggesting an influence from snow melts. Evidence was provided which showed the well documented reduction of cool season (April to October) heavy rainfall from around the time of the Climate Shift onwards. This seemed to be related to a lack of sustained sequences of monthly positive SOIs following the shift. Upper wind data available from some of the heaviest rainfall events showed the presence of anticyclonic turning of the winds between 850 hPa and 500 hPa levels which has been found to be linked with extreme rainfall around the globe.

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