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An investigation of recent orographic precipitation events in northeast Victoria

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This study investigates the spatial and temporal variability of precipitation over northeast Victoria from 2000 to 2005. Using observational data for each month of the year, the elevation dependence of precipitation is analysed over the two distinct mountain ranges (the Strathbogie Ranges and the High Country) that characterise the region. It is found that the rate of increase of precipitation with terrain elevation is proportional to the rainfall at a reference station, representative of the mountain range. Therefore, extreme precipitation events result in pronounced increases in precipitation at the higher elevations. A synoptic classification is also applied to determine which systems are responsible for the precipitation over the region. This classification shows that interacting fronts produce the majority of the precipitation during the cooler months of the year, while cold lows dominate during the warmer months of the year. The consequences of this pattern is briefly investigated in terms of the Southern Annular Mode (SAM), and during 2000-2005 the precipitation from cold lows showed positive correlation with the SAM index, suggesting important large-scale influences on the regional precipitation.

Introduction

Precipitation in northeast Victoria exhibits substantial spatial and temporal variability. The relatively dry northern plains receive a mean annual precipitation of less than 500 mm, and within 125 km the mountainous regions receive over 1600 mm of precipitation annually (Bureau of Meteorology 2000). On average, the winter months (June to August) receive approximately double the rainfall of the summer months (December to February) and, in addition to this seasonal variability, there are substantial fluctuations in precipitation totals from weekly to annual time-scales (e.g. Wright 1989, Hendon et al. 2007). Understanding the spatial and temporal variability of precipitation in this region is crucial due to its important influence on agriculture, water storages, alpine resorts and vegetation.

The spatial variability of precipitation in northeast Victoria is controlled primarily by orographic enhancement. The presence of topography alters incident atmospheric flow, often causing substantial flow deviations in the horizontal and vertical. The resul-

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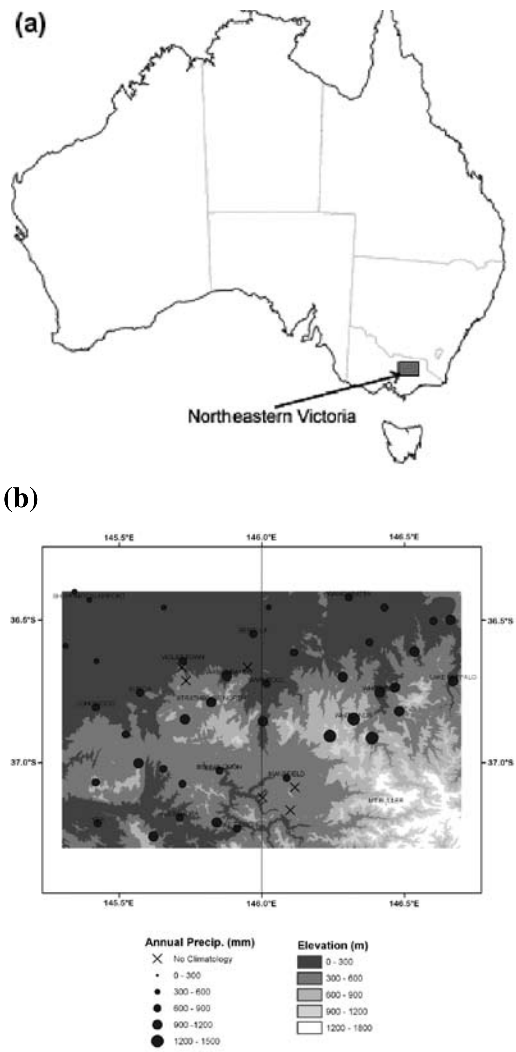
tant vertical ascent can either initiate or enhance the formation of precipitation through a variety of complicated interacting processes (see Smith (1979) and Roe (2005) for reviews). There is an extensive body of literature examining orographic precipitation, and it has long been appreciated that there exist statistical relationships between precipitation totals and terrain elevation (e.g. Henry 1919). These relationships translate to substantial spatial variability in precipitation totals in regions of complex topography, and once defined for specific regions and conditions can be utilised for forecasting and downscaling applications (e.g. Brunsdon et al. 2001). However, these statistical relationships are often location and synoptic situation dependent, and it is one aim of this study to characterise the variability of the elevation dependence of precipitation in northeast Victoria.

The occurrence of Victorian precipitation is controlled by the passage of synoptic weather systems (e.g. Wright (1989), Simmonds et al. (2001) and Pook et al. (2006)). To examine the synoptic control on precipitation, Wright (1989) and Pook et al. (2006) examined the proportion of precipitation from each of their subjectively classified synoptic systems. Wright (1989) calculated the proportion of the cool season (June - September) precipitation, which was recorded at six locations throughout Victoria, including one location in northeast Victoria. Pook et al. (2006) determined the contribution from each synoptic system to the percentage of precipitation falling at various stations in northwest Victoria, between April and October. To date, however, there has been limited research that focuses on orographic precipitation in the mountainous regions of northeast Victoria, which for the purposes of this study is defined by the following coordinates: 37.3°S to 36.4°S and 145.3°E to 146.7°E (see Fig. 1). The paucity of orographic precipitation research in this area is one motivating factor behind this study.

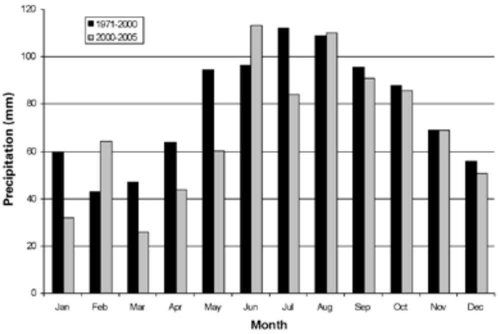
In the present study, northeast Victoria has been divided into two subregions, which are separated by the 146°E meridian (Fig. 1(b)). The Strathbogie Ranges lie to the west of this meridian; here the majority of the topography is lower than 700 m above mean sea level, with a single peak rising to just over 1000 m (derived from Seamless Shuttle Radar Topography Mission 2004). The region to the east of 146°E longitude, locally known as the High Country, rises to the much higher elevation of over 1700 m. These two regions accommodate two distinct mountain ranges, which are separated by a valley on the 146°E meridian. Our study examines year-round precipitation records in northeast Victoria during the years 2000-2005, using the observing network shown in Fig. 1(b). These stations consist of official Bureau of Meteorology sites, and sites operated by volunteer observers (see the Appendix for a complete list).

Fig. 1 **(a) The study area within Australia. (b) The study area showing the climatological precipitation (1971-2000) for each station used; the size of the dot is proportional to the precipitation amount. The relative shadings indicate terrain elevation.**



The climatological precipitation (1971-2000) in northeast Victoria has substantial spatial and seasonal variability (Figs 1 and 2). Figure 2 shows the mean monthly precipitation for five stations that we refer to as our control stations: Benalla, Strathbogie North, Wangaratta, Whitlands and Mansfield; more precipitation is received during the cool season – the seasonal cycle indicates an average station maximum of about 112 mm in July and a minimum of 43 mm during Feb-

Fig. 2 The average monthly precipitation distribution for the five control stations. Shown are climatology (1971-2000) and the 2000-2005 averages.



ruary. When comparing this climatological precipitation to the period of our study (2000-2005) it was noticed that on average 103 mm or 11 per cent less precipitation per year was received in the later period. The decrease in precipitation in the 2000-2005 period is mostly due to decreased falls in autumn.

In this study, we examine the synoptic systems responsible for the precipitation in northeast Victoria between 2000 and 2005. We build on the work completed by Wright (1989), by investigating the synoptic classification for our five control stations. It is believed to be the first study of precipitation for the entire annual cycle in this region, in contrast to the aforementioned studies that have only examined the cooler months of the year. Examining the annual record allows an assessment to be made of possible seasonal change in precipitation patterns associated with changes in synoptic activity.

An important phenomenon controlling the interannual variability of precipitation in southeast Australia is the El Niño-Southern Oscillation (ENSO). The Troup Southern Oscillation Index (SOI), defined as the standardised atmospheric mean sea-level pressure (MSLP) difference between Tahiti and Darwin, is commonly used to determine the phase of ENSO (Troup 1965, McBride and Nicholls 1983, Bureau of Meteorology 2008a). El Niño events are typically accompanied by sustained negative values of the SOI, while La Niña events are typically accompanied by sustained positive values of the SOI. The second important circulation pattern affecting southeast Australian precipitation is the Southern Annular Mode (SAM), which has also been called the Antarctic Oscillation and the High Latitude Mode (Rogers and Van Loon 1982). The SAM index that we use herein is determined from the leading Empirical Orthogonal Function (EOF) of 700 hPa height anomalies poleward of 20°S (Hendon et al. 2007). A positive SAM is associated with anomalous westerly flow at approximately 60°S and anomalous easterly flow at 40°S. A positive SAM has also been found to be associated with a poleward shift in mid-latitude storm tracks and an increase in the number of cut-off lows to the equatorward side of the enhanced ridge at around 45°S (Hendon et al. 2007). Hendon et al. (2007) identified that during the winter months a high SAM index corresponds to a decrease in precipitation in southeast Australia, to the west of the Australian Alps.

The first aim of this study is to investigate the factors that influence the spatial variability of precipitation, which is strongly influenced by the dependence between precipitation and terrain elevation. The second aim is to determine the synoptic controls on the temporal variability of precipitation, from monthly to seasonal scales, in northeast Victoria. First we investigate the elevation dependence of precipitation in the two subregions. Then we examine the variability of precipitation due to different synoptic regimes, and compare the results of the synoptic classification with previous studies. Finally the links between precipitation in this region and the two global indices will be discussed.

The elevation dependence of precipitation

Basist et al. (1994) investigated the elevation, slope, exposure and orientation dependence of annual precipitation for numerous locations around the world, including New South Wales, Australia. It was found that a location's elevation is one of the most influential factors controlling the amount of precipitation received. A common approach is to use linear regression to estimate the rate of increase with elevation of precipitation totals (e.g. Brunsdon et al. 2001), however the estimated parameters are often location and condition dependent.

To investigate the elevation dependence in the two subregions of northeast Victoria, the total monthly precipitation at each available station is plotted against its elevation, and a linear function is fitted to the data via ordinary least-squares regression. This analysis is conducted separately for each month during 2000-2005, and the slope of this linear function, i.e. the rate of increase of monthly precipitation with elevation, is recorded. The histograms describing the statistical distribution of these gradients are shown in Figs 3 and 4 for the Strathbogie ranges and the High Country, respectively. It is apparent that there is substantial variation in the elevation dependence of precipitation, and that the largest gradients usually occur during the cool season

Fig. 3 **Histogram showing the monthly (cool season (June–September), other and all) rate of increase in precipitation per kilometre of elevation for the Strathbogie Ranges during 2000-2005.**

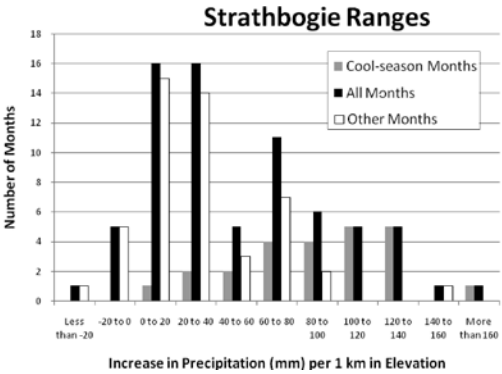


Fig. 4 **Same as Fig. 3, except for the High Country.**

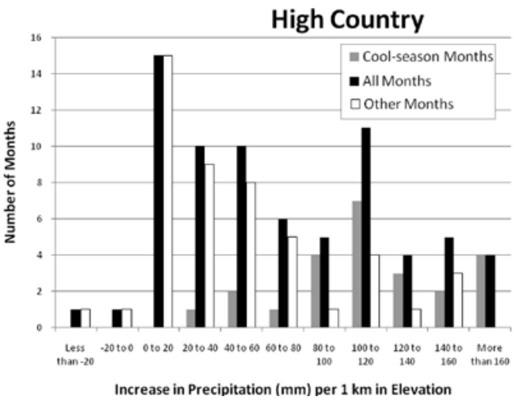


Fig. 5 **Scatter plot of the rate of increase of precipitation per kilometre for the High Country versus the precipitation received in Whitlands for a given month.**

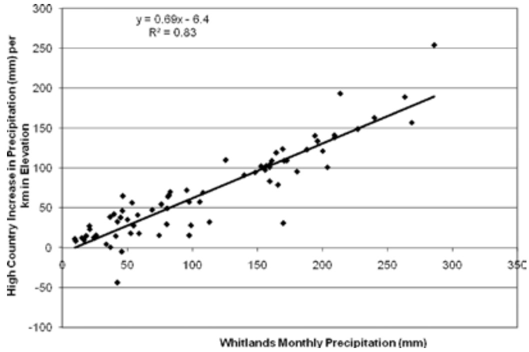
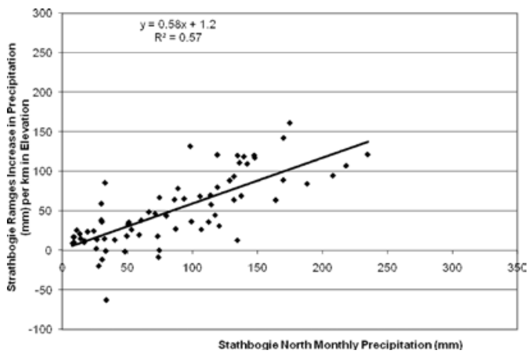


Fig. 6 **Scatter plot of the rate of increase of precipitation per kilometre for the Strathbogie Ranges versus the precipitation received in Strathbogie North for a given month.**



(June-September). Comparison of Figs 3 and 4 also illustrates that there is greater elevation dependence of precipitation in the High Country than in the Strathbogie Ranges. The High Country has a mean rate of increase of 71 mm/km, whilst the Strathbogie Ranges has a mean rate of increase of 52 mm/km. The reason for this could be that the High Country stations, on average, receive approximately 30 per cent more precipitation than those in the Strathbogie Ranges. To investigate this possibility further, Fig. 5 shows the monthly values of the rate of increase of precipitation in the High Country, versus the precipitation received at Whitlands for that month (Whitlands was chosen because, of all the High Country stations used in this study, it was the highest elevation (812 m) station to have a complete precipitation record for this period). There is a well-defined linear relationship between the rate of increase of precipitation with elevation and the precipitation at Whitlands. This suggests that the months when the Whitlands station receives a large amount of precipitation correspond to the months when there is a greater increase in precipitation with elevation. Therefore, because the stations found in the High Country receive more precipitation than the Strathbogie Ranges, Fig. 5 implies that the High Country should have a larger increase in precipitation with elevation.

Figure 6 shows the corresponding trend between the monthly values of the rate of increase of precipitation with elevation for the Strathbogie Ranges versus the monthly precipitation total for Strathbogie North (elevation 551 m). While there is greater scatter about the linear trend in the Strathbogie Ranges (Fig. 6) compared to the High Country (Fig. 5), the slope of both regressions is similar (6.9×10^{-4} and 5.8×10^{-4} m^{-1}, respectively). These linear regressions can be integrated to provide a rainfall/height relation of the form

$$R = R_0 \left(1 + \alpha \left(h - h_0\right)\right), \qquad \ldots 1$$

where R is the monthly rainfall at an arbitrary height, h, and R_0 and h_0 the rainfall and height of a reference station, and α is the slope of the regressions. Equation 1 indicates that the rate of increase in rainfall with height is αR_0. Therefore, not only do higher elevations receive larger precipitation totals, but also large events give rise to a greater rate of increase of precipitation with height, and substantially larger precipitation totals at the highest elevations. The importance of this result is twofold: (a) first, it allows for improved regional downscaling of rainfall predictions from large-scale models, and suggests that simple linear regressions may be inadequate; (b) second, a changing climate that gives rise to larger (smaller) precipitation totals at lower elevations may result in substantial increases (decreases) in the precipitation accumulations at high elevations. Hence, small changes in the seasonal distribution of precipitation and the gross precipitation totals may have a much larger influence at the higher elevations of Victoria's mountains.

It must be noted, however, that the uppermost station used in our analyses falls short of the peak elevations in the High Country. (The reason for this was the poor reliability of the stations above the snow line.) Therefore, caution must be exercised in extrapolating these linear relationships to the highest elevations of the region.

Synoptic classification of precipitation events

In this section, the precipitation events that occurred during the 2000-2005 period are identified and a synoptic classification is performed to determine what type of synoptic systems caused the events. The synoptic classification in this study is based on the scheme devised by Wright (1989), who classified synoptic systems into five different types: interacting fronts, non-interacting fronts, cold lows, heat (warm) lows and post-frontal. In this study, the post-frontal system classification (where post-frontal precipitation occurs in a southerly or westerly airstream behind a cold front) was not used, because these systems produce minimal precipitation over the region (Wright 1989). Furthermore, post-frontal systems are difficult to classify, as they are located immediately behind a front. Each precipitation event investigated in this study will be attributed to the passage of one of the following five defined systems:

I. Interacting front: A significant cloud mass of tropical origin (defined as north of 30ºS) that interacts with a frontal cloudband at some point over the Australian region (e.g. see Fig. 7(a)-(b)).

II. Non-interacting front: A simple frontal cloudband that fails to link up with a tropical cloud mass over the Australian region (e.g. see Fig. 7(c)-(d)).

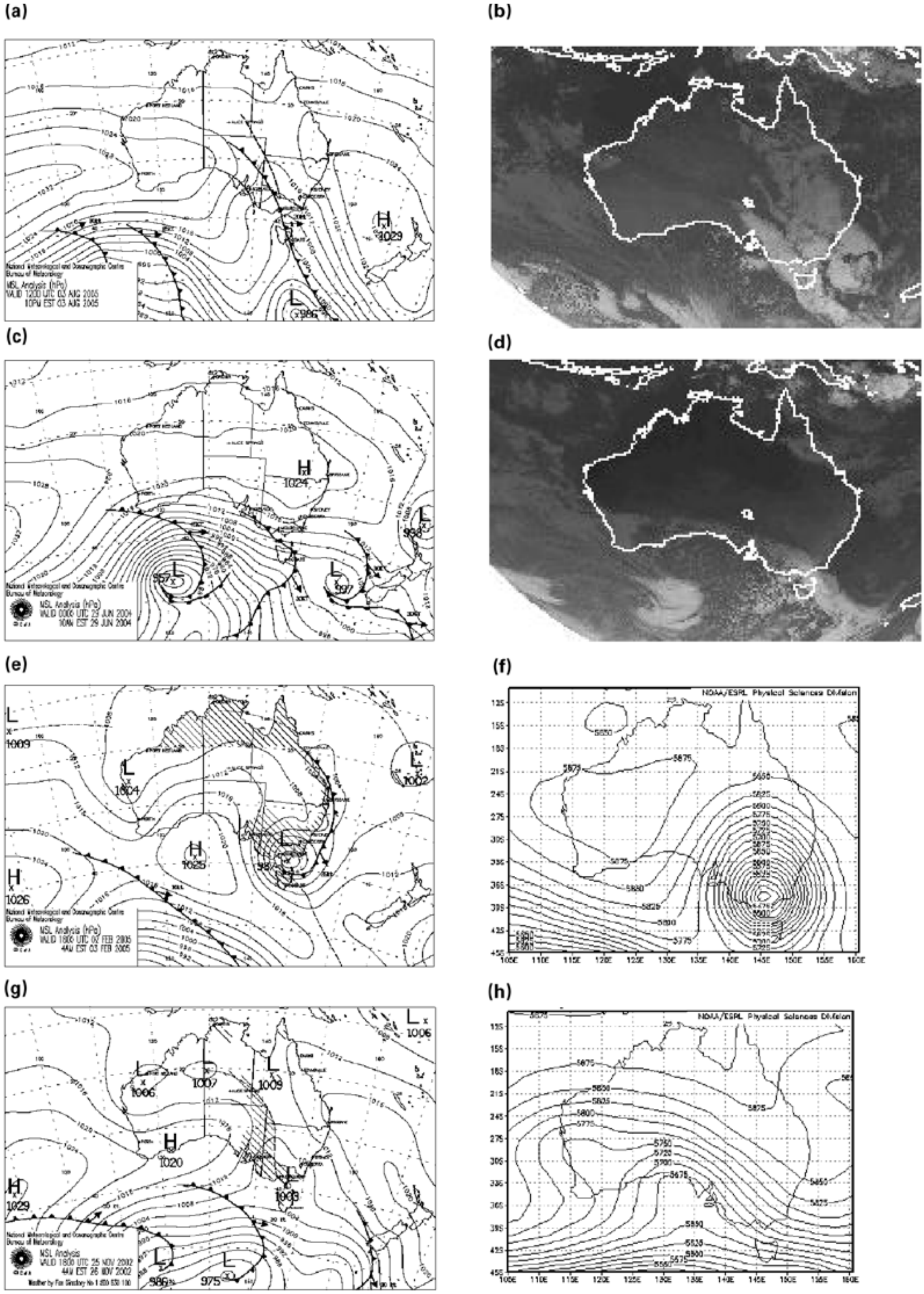
III. Cold low: A cut-off low pressure system that has a cooler core than the surrounding regions. This type of system has two characteristics: the MSLP synoptic chart has a closed cyclonic circulation; and there is a well-defined minimum in geopotential height in the same region as the low pressure system (e.g. see Fig. 7(e)-(f)).

IV. Warm low: A warm low is characterised by a low pressure system in which the centre of the low is warmer than the surrounding regions. The warm low often originates from a heat low which has formed over northern Australia and has moved south over Victoria (Wright 1989) (e.g. see Fig. 7(g)-(h)).

V. Other systems: Any system that does not fit into the first four categories. In this study only two of the 348 systems classified are in this category.

The daily precipitation data from each of five control stations (Benalla, Wangaratta, North Strathbogie, Whitlands and Mansfield) were analysed to identify and classify every precipitation event during the period 2000 to 2005. These five stations were chosen for the completeness of their daily precipitation records and their varied elevations and locations. For the purposes of this study, when any one of the stations received at least 1 mm of precipitation, over one or more continuous days, this was defined as a precipitation event. Each event was then subjectively categorised as being due to one of the five aforementioned synoptic systems by examining surface charts, infrared (IR) satellite images, and the 500 hPa geopotential height. The Bureau of Meteorology online analysis archive (Bureau of Meteorology 2006a), which shows mean sea-level pressure and (subjectively) analysed fronts, was used for the surface analysis. The daily mean geopotential height (average of six-hourly data) was obtained from the NCEP Operational Analysis (NOAA/OAR/ESRL PSD 2006), and the satellite IR imagery (GOES-9) was obtained from the NOAA Satellite and Information Service (NOAA Satellite and Information Service 2006).

Fig. 7 **(a) Mean sea-level pressure (MSLP) chart at 1200 UTC 3 August 2005. (b) IR satellite image at 1200 UTC 3 August 2005. (c) MSLP chart at 0000 UTC 30 June 2004. (d) IR satellite image at 0000 UTC 30 June 2004. (e) MSLP chart at 0600 UTC 3 February 2005. (f) Mean 500 hPa geopotential height on 3 February 2005. (g) MSLP chart at 1200 UTC 25 November 2002. (h) Mean 500 hPa geopotential height on 25 November 2002. MSLP charts are from the Bureau of Meteorology, satellite images are from GOES-9, and the geopotential height is from NCEP.**



In order to consistently categorise the precipitation events, a set of guidelines was determined. Often synoptic systems occurred sequentially, with no dry days between events, in which case the original event's precipitation may be produced by more than one synoptic system. In this case the original event was split into multiple events for classification, based on an examination of the MSLP, geopotential height, and satellite data. Another factor that had to be taken into account was the observers' occasional absences from weather stations, which resulted in precipitation accumulating over a number of days. To circumvent this problem, when an observer was noted as absent, precipitation data from surrounding rain gauges were used to categorise the event. This scenario, however, occurred infrequently and would therefore have minimal impact on the results.

Table 1 shows the annual precipitation averaged over the five reference stations and the contributions to that total from each synoptic type, and illustrates that there is considerable annual variability in the precipitation totals and in the contribution from each synoptic system in northeast Victoria. The two synoptic types that are always the two largest contributors are interacting fronts and cold lows. Non-interacting fronts and warm lows contribute far less precipitation to the yearly totals. In the driest year (2002), contributions from both interacting fronts and cold lows were substantially smaller than the other years, with the contribution from cold lows down considerably. Only two events in the six-year period were assigned to the other classification; because of this minor contribution only the four remaining synoptic types will be considered in this study.

The proportional contributions from each synoptic type (except other) to the monthly precipitation are shown in Figs 8 and 9. These figures, which show both the average and the maximum and minimum contributions of the five stations for each month, indicate that the statistics are, for the most part, very similar across all five stations. This similarity implies that the precipitation arises from synoptic-scale systems. The warmer months (November-February) show the largest spread among the stations, suggesting the importance of mesoscale variability at those times. Furthermore, during the warmer months (non cool season) the increase in precipitation with elevation was generally less than in the cool season, had larger variance than the cool season, and in a number of the non cool season months the precipitation actually decreased with elevation.

Figure 8(a) shows that interacting fronts produced the majority of precipitation between the months of March and September, with a maximum (approximately 70-80 per cent) occurring in autumn (March-May). These months also had little precipitation associated with non-interacting fronts (Fig. 8(b)), indicating that in autumn circulation patterns allow most mid-latitude fronts to link up with tropical moisture. During the winter months the proportion of precipitation from the interacting fronts decreases slightly, with a corresponding increase in precipitation from non-interacting fronts. Between November and April there is almost no precipitation from non-interacting fronts. Further, the northernmost stations (Benalla and Wangaratta), received the lowest proportion of precipitation from non-interacting fronts (not shown). This could be attributed to the fact that precipitation from non-interacting fronts may be associated with a more southwesterly flow, and if this were true much of the moisture would be removed during the passage of the air mass northwards.

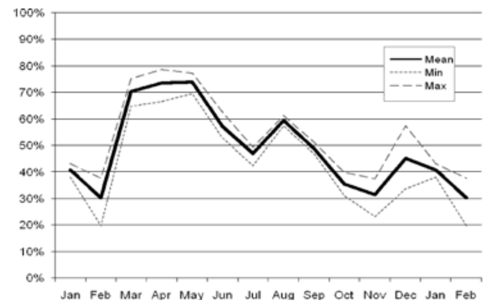
Cold lows produce the most precipitation in the summer months (December-February), with a pronounced maximum in precipitation in February (Fig. 9(a)). Note that this peak does possess a contribution from the extreme precipitation event that occurred in February 2005, yet a maximum remains present even if this year is excluded. Figure 9(b) shows that between 2000 and 2005 warm lows produced no precipitation during autumn (March-May) and winter (June-August) and only produced significant precipitation during spring (September-November) and contributed a small proportion (1-10 per cent) of the summer (December-February) precipitation.

Table 1. Annual precipitation (in mm) from each synoptic system (averaged over the five control stations), the numbers of each system affecting northeast Victoria and the percentage of the annual precipitation from that synoptic type.

Year	2000			2001			2002			2003			2004			2005		
	No.	mm	%	No.	mm	%	No.	mm	%	No.	mm	%	No.	mm	%	No.	mm	%
Interacting fronts	37	618.1	63.8%	25	444.8	59.9%	26	324.3	57.7%	29	351.9	36.1%	29	336.6	35.3%	35	414.0	41.7%
Non-interacting fronts	7	28.7	3.0%	12	51.8	7.0%	11	82.2	14.6%	9	116.4	11.9%	12	76.1	8.0%	6	59.6	6.0%
Cold lows	12	220.0	22.7%	15	227.9	30.7%	11	97.8	17.4%	12	425.0	43.6%	17	336.0	35.3%	13	467.8	47.2%
Warm lows	3	99.4	10.3%	3	15.4	2.1%	3	56.7	10.1%	4	80.3	8.2%	2	3.6	0.4%	3	49.3	5.0%
Other	1	0.8	0.1%	0	0.0	0.0%	0	0.0	0.0%	0	0.0	0.0%	0	0.0	0.0%	1	0.6	0.1%
Total	60	968.8		55	742.5		51	561.6		54	974.7		60	953.3		58	991.9	

Fig. 8 The mean proportion of precipitation from: (a) interacting fronts; and (b) non-interacting fronts for each month. Shown is the mean across the five control stations with the maximum and minimum of the stations shown by the dashed lines. A 14-month period is shown in order to show the summer season more clearly.

(a)



(b)

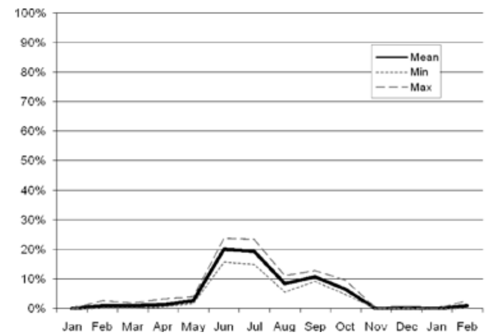
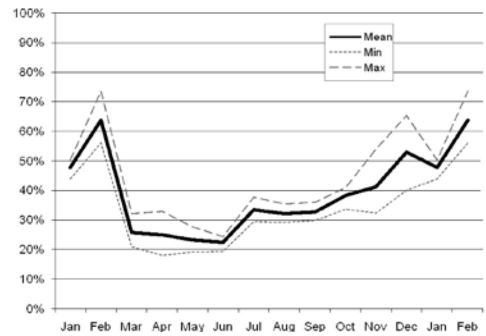


Fig. 9 Same as Fig. 8, except: (a) cold lows; and (b) heat lows.

(a)



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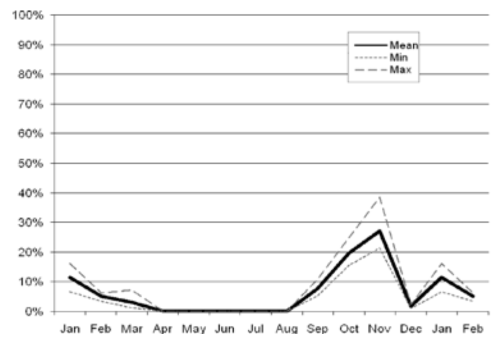
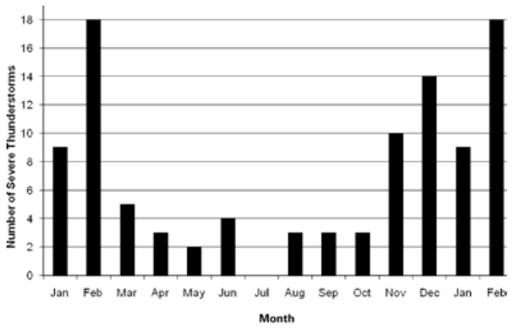


Along with the daily precipitation data, we also examined the monthly occurrence of thunderstorms over the region between 2000 and 2005. The identification of thunderstorms was achieved by using the Monthly Significant Weather Summaries (MSWS) (Bureau of Meteorology 2008b). Whenever the MSWS mentioned severe thunderstorm activity occurring in the north-central, northern country or northeastern Victorian regions, then a storm was noted in order to develop thunderstorm statistics over the period in question (Fig. 10). The MSWS does not, however, capture all non-severe thunderstorm events, as the summaries only cover days when a severe thunderstorm was observed somewhere, although not necessarily in the area of interest. A comparison of Figs 9(a) and 10 suggests a relationship between the monthly distribution of thunderstorm events and the proportion of precipitation from cold lows. By definition, cold lows are associated with cold air aloft, which leads to increased instability; as a result the chance of thunderstorms is increased and higher precipitation totals would be expected. This result implies that the precipitation derived from cold lows could be associated with thunderstorm activity, which may account for the greater (mesoscale) variability in cold-low precipitation between stations during the active months (Fig. 9(a)).

Probably the most important conclusion that can be derived from these results is that the events with the largest precipitation accumulations are associated with the largest rates of increase in precipitation with elevation; these events mostly occur in the cool season (see Figs 3 and 4), which is dominated by interacting fronts.

Fig. 10 Monthly distribution of severe thunderstorms over northern Victoria between 2000 and 2005.



Comparison with climatology and previous studies

In this section, the results of the synoptic classification are compared with previous studies to characterise the differences that may have contributed to the 11 per cent reduction in northeast Victorian precipitation during 2000-2005.

Wright (1989) classified the cool season (June to September) precipitation events that occurred at the Wangaratta station for the period 1971 to 1982. In May 1987 this station closed and was replaced by the Wangaratta Aero AWS, 6 km south of the city, in a more rural position, at a similar elevation. We decided, however, that the minor change in location was not of sufficient importance to preclude a comparative study (Table 2). This comparison suggests that the proportion of cool season precipitation from fronts in Wangaratta decreased by about five per cent between these two periods, and the major contributors to this decrease were non-interacting fronts. There is a corresponding relative increase in the precipitation from cold lows. Although no direct comparison between this study and Wright's (1989) study can be made for the autumn months, Fig. 2 indicates that the largest reduction in rainfall occurred in autumn. Figure 8(a) implies that a reduction in autumn rainfall is likely caused by a reduction in precipitation sourced from interacting fronts.

Pook et al. (2006) examined the proportion of precipitation from various synoptic systems that affected northwest Victoria between 1970 and 2002 for the period April to October, however, they used a different classification scheme from that adopted by Wright (1989) with only three synoptic categories: fronts, cut-off lows and others. The frontal classification used by Pook et al. (2006) included both interacting and non-interacting fronts, and the cut-off lows were equivalent to the cold lows defined earlier. Despite these differences in methodology we can compare the results for the years 2000-2002 between the two regions (Table 3). It is clear that northwest Victoria receives a much higher proportion of precipitation from cold lows than does northeast Victoria. Wright (1989) noted this occurrence during the cool season, and suggested that Mildura receives only a small proportion of precipitation from fronts due to its inland location.

In summary, during the study period (2000-2005), it appears that the precipitation derived from interacting fronts in autumn and non-interacting fronts in winter is marginally smaller than that in the 1971-1982 period. This change suggests that in recent years the cool season precipitation patterns in northeast Victoria have become more akin to those in northwest Victoria with an increased proportion of precipitation being due to cold lows. It must be emphasised, however, that the short sample size of the twenty-first century data places substantial uncertainty on these conclusions. Nevertheless, in the next section we examine large-scale circulation patterns that may be consistent with these changes.

Table 2. Synoptic classification of cool season precipitation (percentage of total) from Wright (1989) and this study.

	This study 2000-2005 Wangaratta Aero	*Wright (1989) 1971-1982 Wangaratta*
Interacting fronts	54.7%	47%
Non-interacting fronts	12.1%	18%
Post-frontal	-	6%
All fronts	**66.8%**	**71%**
Cold lows	30.4%	24%
Warm lows	2.4%	5%
All cut-off lows	**32.8%**	**29%**

Table 3. Synoptic classification of April to October precipitation from this study and Pook et al. (2006).

Year	*This study Benalla*		*Pook et al. (2006) NW Victoria*	
	Fronts	*Cold lows*	*Fronts*	*Cold lows*
2000	73%	16%	31%	42%
2001	63%	37%	35%	56%
2002	76%	22%	46%	46%

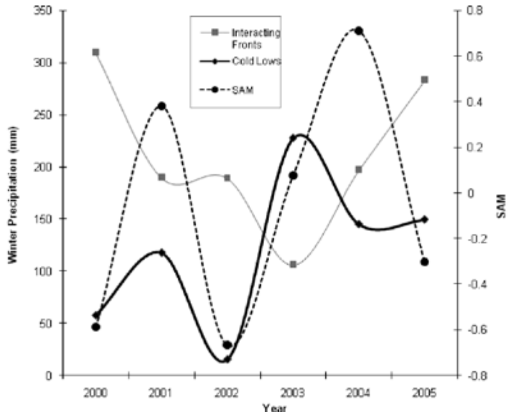
Relationship between Victorian precipitation and the large-scale circulation

The previous sections illustrate the importance of synoptic-scale disturbances, viz. cold lows and interacting fronts, in producing much of the precipitation in our region of interest. Hence, changes in the frequency or intensity of these systems will influence precipitation totals; large-scale modes of variability, such as the SAM, may influence synoptic patterns and hence modify regional precipitation. Hendon et al. (2007) found that a high SAM index was associated with a decrease in precipitation over the western slopes of the southeast Australian ranges during winter. In order to explore the influence of the SAM on the precipitation from our synoptic types, Fig. 11 shows the cool season average of the SAM index (obtained from NOAA/National Weather Service 2008) and the cool season precipitation received from interacting fronts and cold lows between 2000 and 2005. This comparison indicates that in our region of interest the variability in precipitation derived from cold lows is coupled to the SAM, with a higher amount of precipitation from cold lows associated with a high SAM index (correlation of +0.59). This result is consistent with an increase in the number of cut-off lows to the north of the enhanced ridge at around 45°S that occurs when the SAM index is positive (Hendon et al. 2007). Of course, due to the short period of analysis, this relationship is not statistically significant, but suggestive of an important large-scale mechanism controlling precipitation on the regional scale.

Figure 11 also shows that the amount of precipitation from interacting fronts is anti-correlated with the SAM index (correlation coefficient –0.45), but in this case the relationship is far from convincing. This result is, however, consistent with a poleward shift of the mid-latitude storm track during positive SAM events, which would reduce the influence of fronts on southeast Australia.

In addition to the SAM, the phase of ENSO has important influences on southeast Australian rainfall (Wright 1988; McBride and Nicholls 1983). During our period of study, 2002-2003 featured a low SOI and these years were classified as El Niño conditions (Bureau of Meteorology 2006b). The 2002-2003 cool season precipitation from interacting fronts is reduced in comparison to the other years (Fig. 11), and there is also a slight increase in the precipitation from non-interacting fronts (not shown). (However, it must be noted that El Niño conditions had halted by the winter of 2003). With this in mind, we hypothesise that the circulations associated with El Niño may thwart the interaction between mid-latitude frontal systems and tropical moisture, giving rise to fewer interacting fronts and more non-interacting fronts. These non-interacting fronts are less efficient at producing precipitation than their interacting counterparts, resulting in less total precipitation in northeast Victoria.

Fig. 11 The annual variability in the (five-station mean) cool season precipitation from interacting fronts, cold lows, and the cool season average of the SAM index.



These brief comparisons highlight the importance of large-scale controls on the frequency and occurrence of synoptic-scale systems, which in turn influence the variability of northeast Victorian rainfall. The period of our analysis is clearly too short to allow robust conclusions to be made, yet this analysis demonstrates that these interactions are worthy of future study.

Conclusions

Several aspects of the precipitation patterns in northeast Victoria have been considered in this paper. The following are the key findings.

(a) As is true in many parts of the world, the monthly precipitation totals in northeast Victoria exhibit a linear dependence on elevation. While the gradient of these relationships shows much temporal variability, these gradients are strongly correlated with the total monthly precipitation at a high-elevation reference station. This relationship not only explains the larger precipitation totals in the High Country compared with the Strathbogie Ranges, but also has important consequences for future climate. Any trends in the large-scale precipitation totals may be amplified at high elevations in northeastern Victoria. For example, it has been suggested by Basher et al. (2001) that, due to climate change, by the year 2030 extreme precipitation events in Australia will be more frequent and severe. Figures 5 and 6 imply that any increase in the severity of extreme precipitation events would result in possibly devastating increases in precipitation at the higher elevations. This finding will need to be considered in the future with respect to the flood monitoring of catchments fed by these high elevations, especially in the High Country. Alternatively, if the opposite trend were to occur in a changing climate, i.e., a reduction in large precipitation events, the highest elevations might suffer with significantly reduced rainfall totals.

(b) A classification of precipitation producing synoptic systems, based on a scheme devised by Wright (1989), shows that fronts that interact with the tropics, i.e. interacting fronts, produce the majority of the precipitation from March - September, while low pressure systems with cold cores, i.e. cold lows, dominate during the warmer months (October – February); the other two types of systems (non-interacting fronts and warm lows) make a comparatively small contribution to the precipitation. The most important conclusion drawn from this analysis is that any long-term variation in the frequency or intensity of these two important sources would impact strongly on the seasonal rainfall patterns. Longer time-scale variations in these important synoptic systems can be inferred from reanalysis products (e.g., Simmonds and Keay 2000) or climate model projections.

A comparison between the 2000-2005 period and climatology (Fig. 2) indicates that the largest changes in recent precipitation occurred in autumn, during which period the rainfall is mainly controlled by interacting fronts (Fig. 8(a)). Thus, the autumn break rains have been reduced in the recent period (2000–2005). This recent pattern has very important consequences for agriculture, and in particular grazing where farmers have a choice between autumn and spring calving. In the current pattern, the former alternative now appears much less desirable.

(c) The connections between the large-scale modes of variability and the regional variations in precipitation have also been briefly discussed, and clearly form a crucial pathway of interaction between the global and regional scales. These large-scale circulation patterns modify the number of precipitation producing systems, the efficiency of those systems in producing rainfall, and the seasonal distribution of those systems. Yet, we are mindful that the twenty-first century precipitation record is short. Further investigation of the temporal variability in precipitation over northeast Victoria is required to determine the important relationships, and is the subject of continuing research. Further testing of these relationships would benefit from a greater number of high-quality stations, especially in the High Country.

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Appendix 1

List of stations

The Strathbogie Ranges stations

BoM Station No.	*Name*	*Elevation (m)*	*Latitude (°S)*	*Longitude (°E)*
81095	MURCHISON (ARCADIA (SUNNYVILLE))	125	36.59	145.31
81034	MOOROOPNA	114	36.40	145.34
81125	SHEPPARTON AIRPORT	116	36.43	145.39
82083	LONGWOOD	181	36.81	145.42
88031	HIGHLANDS (GLENTANNAR)	579	37.07	145.42
81033	MOLKA (LOWANA)	138	36.64	145.42
88067	YEA (POST OFFICE)	170	37.21	145.42
82096	CREIGHTONS CREEK (BARONGA)	286	36.90	145.52
82089	TERIP TERIP	552	37.00	145.57
88163	ALEXANDRA (CRYSTAL CREEK)	337	37.26	145.62
88120	KANUMBRA (BRILLIANT ESTATE)	286	37.02	145.65
81007	CANIAMBO	140	36.46	145.66
88001	ALEXANDRA (POST OFFICE)	233	37.19	145.71
*	TOM COCKER	180	36.67	145.72
82049	VIOLET TOWN	176	36.64	145.72
88153	SPRING CREEK BASIN TWO	350	37.08	145.72
82042	STRATHBOGIE	507	36.85	145.73
*	TREVOR BLAVER	319	36.71	145.73
82043	STRATHBOGIE NORTH	551	36.79	145.82
88164	EILDON FIRE TOWER	638	37.21	145.84
88007	BONNIE DOON GARAGE	311	37.03	145.85
82134	WARRENBAYNE	227	36.70	145.88
88023	LAKE EILDON	238	37.23	145.91
82002	BENALLA (SHADFORTH STREET)	169	36.55	145.97
*	JOHN BYE	352	37.12	146.00
*	PETER LLOYD	361	36.97	146.00

The High Country stations

BoM Station No.	*Name*	*Elevation (m)*	*Latitude (°S)*	*Longitude (°E)*
*	PETER LLOYD	361	36.97	146.00
82107	LIMA SOUTH (LAKE NILLAHCOOTIE)	276	36.86	146.00
82061	SWANPOOL (TIREE)	211	36.72	146.02
81116	CHESNEY VALE (LAKE MOKOAN NO 1)	170	36.46	146.02
83019	MANSFIELD (POST OFFICE)	318	37.05	146.09
*	MARK CALVERT-JONES	415	37.17	146.10
82109	MOLYULLAH (KILLANOOLA)	199	36.61	146.11
*	DAVID ESSER	347	37.09	146.12
83000	ARCHERTON	909	36.91	146.24
82033	MYRRHEE (JOELYN)	273	36.70	146.28
82138	WANGARATTA AERO	150	36.42	146.31
83032	WHITLANDS (BURDER'S LANE)	812	36.85	146.32
82032	MOYHU	178	36.58	146.38
83074	LAKE WILLIAM HOVELL RESERVOIR	427	36.91	146.39
83031	WHITFIELD	238	36.75	146.41
82029	MILAWA BROWN BROS	160	36.46	146.4
83083	EDI UPPER	356	36.74	146.47
83065	CHESHUNT EURANGIE PARK	366	36.82	146.48
82009	CARBOOR	244	36.61	146.54
82055	WHOROULY	194	36.50	146.60
83079	LAKE BUFFALO	298	36.71	146.67

* Denotes a private (non-BoM) station
COMAN was included in both regions as it was on the dividing 146 degree meridian