On the decline of wintertime precipitation in the Snowy Mountains of South-Eastern Australia

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ABSTRACT

Data from a precipitation gauge network in the Snowy Mountains of South-Eastern Australia has been analysed to produce a new climatology of wintertime precipitation and airmass history for the region in the period 1990-2009.

Precipitation amounts on the western slopes and in the high elevations (> 1000 m) of the Snowy Mountains region have experienced a decline in precipitation in excess of the general decline in South-Eastern Australia. The contrast in the decline east and west of the ranges suggests that factors influencing orographic precipitation are of particular importance.

A synoptic decomposition of precipitation events has been performed, which demonstrates that about 57% of the wintertime precipitation may be attributed to storms associated with "cut-off lows" (equatorward of 45° S). A further 40% was found to be due to "embedded lows", with the remainder due to Australian east coast lows and several other sporadically occurring events. The declining trend in wintertime precipitation over the past two decades is most clearly seen in the intensity of precipitation due to cut-off lows, and coincides with a decline in the number of systems associated with a cold frontal passage.

Airmass history during precipitation events was represented by back trajectories calculated from ECMWF Interim Reanalysis data, and statistics of air parcel position were related to observations of precipitation intensity. This approach gives insight into sources of moisture during wintertime storms, identifying "moisture corridors" which are typically important for transport of water vapour from remote sources to the Snowy Mountains region. The prevalence of these moisture corridors are associated with the Southern Annular Mode, which corresponds to fluctuations in the strength of the westerly winds in South-Eastern Australia.

1. Introduction

Recent declines in wintertime snowpack in the Australian Snowy Mountains (Nicholls 2005) demonstrate the vulnerability of such alpine systems to climate change. Economic consequences of declining snowpack include decreased runoff into the major river systems of the Murray-Darling Basin, as well as adverse impacts on the tourism industry linked to wintertime recreation. The declining snowpack also threatens thermally regulated habitats for a variety of native species. Using wintertime maximum and springtime (first October measurement) snowpack depths from 1962 to 2002 as indices, Nicholls (2005) found 10% and 40% declines respectively, which could be explained by a weak decline in precipitation and a strong warming trend in the region. Major precipitation events resulting from synoptic activity, "specifically the depth and frequency of systems bringing strong south westerly flow across the south east of the continent" were identified as a controlling factor in the peak annual values, whereas warming was found to be the most important mechanism in the decline in springtime snowpack.

South-Eastern Australia has been in an intermittent drought for much of the two decades to 2010 (Murphy and Timbal 2008, Timbal 2009), with severe drought in 1991-95, 2002-03 and 2006. The nature of the decline appears to be a shift to lower precipitation amounts between 1997 and 2009, occurring principally in the autumn/winter months. A decline in cool season precipitation of 15% over the period 1958-2007 has been identified for rainfall gauges south of 30° S (Nicholls 2010), and is principally attributed to changes in the Southern Annular Mode (SAM).

Precipitation in these alpine regions is *orographic* in the sense that it is enhanced in some way by the influence of topography on the meteorology of the area. Mountainous barriers such as the Great Dividing Range impede the flow of moist air, and depending on conditions such as the thermodynamic profile and flow-speed/topography relations (Houze 1993), a lifting mechanism is provided. Generally this serves to enhance rainfall during widespread precipitation events, but it is not uncommon to observe clouds over the ranges when conditions are clear elsewhere.

Orographic precipitation in Australia has received little attention in comparison to mountainous regions of Europe (e.g. Rotunno and Houze 2007, Volkert and Gutermann 2007) North America (e.g. Stoelinga et al. 2003, Ikeda et al. 2007) and New Zealand (Wratt 1996), where intensive observational studies have been conducted with the aim of characterising surface precipitation distribution and improving microphysical parametrisations, amongst other things. This is perhaps understandable given that the contribution of orographic precipitation to the Australian annual total is relatively small, owing to the relatively low profile of the Great Dividing Range and the absence of a nearby warm moisture source upwind of the range. Nevertheless, the importance of orographic precipitation in these mountain ranges to the economy and ecology of South-Eastern Australia justifies further consideration.

The amount of precipitation brought by individual synoptic systems is highly variable and depends on meteorological and topographical factors. Wright (1989) described five major synoptic types (two frontal, a post-frontal, and two cyclonic low categories) for the south-eastern state of Victoria for the winter period of June–September. The relative contribution to daily precipitation statistics of each type was found to vary substantially in different geographical regions, and in particular notes that the influence of frontal systems was reduced in regions leeward of topographical barriers. Pook et al. (2006) classified daily precipitation in the "cool-season" (April–October) in Western Victoria, according to "frontal" and "cut-off low" categories. This analysis found that at least half of the precipitation, and that 80% of all daily records greater that 25 mm, could be attributed to cut-off lows, emphasising the importance of these systems for precipitation in South-Eastern Australia. Specifically considering precipitation in the Victorian high country, Landvogt et al. (2008) showed that precipitation was produced by a variety of synoptic meteorological conditions; with about half of the precipitation sourced from pre-frontal rainfall and the remaining half almost equally shared between post-frontal rainfall and the passage of low pressure systems over the region.

Back trajectory analyses have been used in analyses of airmass history for some time. They are typically used to investigate atmospheric pollution transport, but have more recently been used in conjunction with evapotranspiration and precipitation derived from gridded analyses to identify moisture sources for precipitation in river basins, differentiating between advective transport and local recycling of moisture (e.g. Dirmeyer and Brubaker 1999, Stohl and James 2005). They are an attractive analytical tool because they are computationally inexpensive to produce and software to calculate them is readily available, for example the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model (Draxler and Hess 1998). Consisting of simply a set of hourly positions with a small amount of meta data, trajectories require little storage, so it is feasible to build climatologies over long periods for multiple locations.

The objectives of the present work are to present a climatology of wintertime (May–September) precipitation in the alpine regions of South-Eastern Australia, and to characterise the airmass history during precipitation events. Particular attention is given to the Snowy

Mountains region, the highest of the ranges along the divide, because of the availability of surface precipitation data not previously utilised. Seasonal patterns of precipitation amount and variability are discussed, and a synoptic decomposition of all winter precipitation events for the period 1990-2009 has been performed. A climatology of back trajectories has been coupled with the precipitation record to characterise the airmass history during wintertime storms to highlight the importance of the role of regional circulation in seasonal precipitation amounts.

2. Seasonal and climatic features of a high-density precipitation gauge network in the Snowy Mountains

The Great Dividing Range is Australia's most significant mountain range, and extends along the entire eastern coast of the continent. The Snowy Mountains form the highest section of the range, a rugged barrier between the south-eastern coastal regions and the extensive lowlands of the Murray-Darling basin to the west (figure 1). They consist of the only peaks above 2000 m on the Australian continent, the highest point being Mt Kosciuszko at 2228 m, and cover some 2500 km^2 of terrain above 1400 m. They have formed an important catchment for South-Eastern Australia since the development of the hydroelectricity and irrigation complex known as the Snowy Mountains Scheme, with eastward flowing waters redirected inland beneath the ranges to the Murray and Murrumbidgee Rivers.

a. Precipitation data sources

The Australian Bureau of Meteorology (BOM) has a number of daily (manual) precipitation observation sites and an increasing number of Automatic Weather stations (AWS) in the wider Snowy Mountains region, but the density of the network in the high elevation regions above 1000 m is very low. Only two AWS operate for the period 1990–2009, with an additional two manual observation sites at the major ski centres.

Furthermore, the measurement of precipitation in this environment is notoriously difficult. Especially in the winter months (May–September), high winds and frozen hydrometeors frequently result in under-reporting of precipitation amount, and the remote nature of the Snowy Mountains region makes access for equipment maintenance challenging. It is not uncommon to find extended periods of missing data in the observational records, and there may be substantial disagreement, even between gauges that are closely located. To address the shortcomings of the existing alpine precipitation data, one of the primary purposes of this paper is to present and discuss an augmented precipitation dataset spanning the period 1990–2009, consisting of the established BOM daily precipitation observations and an independent network of precipitation gauges maintained by the operators of the Snowy Mountains Scheme.

1) Bureau of Meteorology gauges

Precipitation records from all BOM gauges between 35° and 37° S and east of 146.5° E (figure 2) were quality controlled to ensure an adequate number of observations were available. At least five years of data during each of which more than 85% of daily wintertime observations were required for each site, and the span of these data was further required to be at least ten years. In order to overcome the effect of missing data on monthly and seasonal totals, precipitation accumulations for each gauge were estimated from the average daily precipitation amounts for a given month. At least 85% of days were required to make each estimate, with months and seasons rejected if this criterion was not met.

2) Snowy Hydro gauges

The Snowy Hydro Ltd. (SHL) gauges form a network of heated tipping bucket gauges in the alpine regions of the Snowy Mountains, with locations and data availability for these gauges provided in table 1. The first gauge was established in 1989, and the network grew to twelve gauges providing hourly precipitation from 1995 to the present date. The hourly data was quality coded to indicate manual corrections and equipment faults, and has been cumulated for each 24 hour period to 9 am Local Standard Time (23 UTC) on each day in the analysis period. About 90% of the combined daily record for these gauges was available once days with missing or QC-flagged data were rejected. At two sites (Cabramurra and Guthega P.S.) a BOM manual gauge had previously been maintained, and the precipitation record was extended back to 1990 using a conversion based on regression of the daily precipitation values during the overlapping period.

Daily precipitation amounts were accumulated to give monthly and seasonal totals in the same manner as for the BOM gauges.

3) Grouping of precipitation gauges

Daily precipitation records from the gauges with the highest elevations were found to be generally very well correlated with one another. A group of ten "high elevation" gauges from both the BOM and SHL networks (table 1) was chosen based on elevation, location near the main range and completeness of data to form a *daily precipitation index* for the alpine region. This index is the best available indication of precipitation amount in the high elevation regions, with at least three gauges contributing to the average on any given day.

All of the precipitation records were correlated with the alpine daily precipitation index to determine their comparability, with correlation coefficients contoured in figure 2. Gauges with correlation coefficients of greater than 0.7, generally located along the lower slopes and to the west of the Snowy Mountains region were selected to form a "western slopes" group of 38 gauges (including one SHL gauge). To the east of the mountains, daily precipitation was generally poorly correlated to the alpine average, as these regions are generally located within the rain shadow cast by the mountains during the predominant westerly systems. A selection of 21 nearby gauges located to the east (including two SHL gauges) form the "eastern slopes" group.

b. Precipitation averages for the period 1990–2009

Figure 3 shows monthly precipitation averages for the 20 year analysis period. The high elevation and western slopes gauges have a clear June–September maximum, with precipitation amounts roughly double for the high elevation gauges. Precipitation to the east of the ranges follows a substantially different pattern, with winter precipitation amounts substantially lower than for the western group despite the higher average elevation of the eastern group (about 860 m) compared to the western group (about 645 m). The summer values for the eastern and western groups are essentially the same, suggesting that topographic effects play a much more important role in wintertime. For comparison, the precipitation amounts for the gauges used by Pook et al. (2006) have also been included, demonstrating that precipitation amounts are a factor of four to six times that for the upwind plains of western Victoria.

Mean wintertime precipitation for the analysis period is plotted against station elevation in figure 4. The eastern gauges show generally lower precipitation amounts and very little dependence on elevation, as may be expected from their location in the rain shadow of the main range. It is natural to treat the western slopes and high elevation gauges together, and a strong relationship between station elevation and winter precipitation (35.6 mm per 100 m) is apparent. There is a degree of variability which should be expected in a complex topographic environment.

c. Precipitation trends and elevation

Precipitation in South-Eastern Australia has been demonstrated to have declined from long-term values during the analysis period, with cool season precipitation affected by a shift towards lower values from about 1997 (Murphy and Timbal 2008). This type of shift can not be verified in a 20 year time-series, so instead linear trends over the analysis period are used to characterise the decline for the Snowy Mountains region. Figure 5 shows the May–September average precipitation accumulation for each of the three groups. Of note are the particularly dry periods in 1994 and 2006 for all groups, which are associated with extended El-Niño conditions. Wintertime precipitation for the high elevation gauges correlates quite closely with the western slopes gauges ($r = 0.89$), but as expected, is less clearly related to the eastern regions ($r = 0.66$). Incidentally, the correlation coefficient between May–September precipitation with the mean for all of the 117 mainland BOM "high quality" gauges (Lavery et al. 1997) south of 30° S and east of 135° E is also very high ($r = 0.85$), suggesting that the same drivers are affecting wintertime precipitation overall in South-Eastern Australia.

Strong negative trends are evident in the wintertime precipitation amount for both the high elevation and western slopes. The value of the trend for the high elevation sites is -26 mm per year, amounting to 520 mm (-43%) over the analysis period, and for the western slopes it is -11 mm per year, or about -37%. Both of these declines are substantially stronger than that reported by Murphy and Timbal (2008) (-14% between 1997 and 2006 compared to the long-term average), as well as that apparent in the south-eastern "high quality" BOM network, which experienced an average May–September decline of 28.3% over the same period. The nearby eastern slopes, in contrast, have a rate of decline of slightly less than 26%, suggesting that possibly orographic influences for both the lower western slopes and the high elevation sites have been impacted.

When considered on a gauge-by-gauge basis, some subtle features of the precipitation decline become apparent. The first panel of figure 6 shows the regression coefficient for the 20-year decline plotted against the mean wintertime precipitation for each site. If the decline were consistent across the board, the data points would form a coherent relationship. This appears to hold for the eastern and western slopes, where there are very few outliers. However, the high elevation data are very scattered, suggesting that the decline is not simply proportional to the precipitation amount for these gauges.

Plotting the decline against station elevation (second panel of figure 6), gives a fit that is better overall, and the scatter for the high elevations is substantially reduced. The linear fit for this relationship has a slope of -1.45 mm per 100 m per year, and with a correlation coefficient of 0.79 it is a highly significant trend ($P < 0.001$). When the *relative* decline is plotted against station elevation, the resulting trend (-0.057% per 100 m per year with $r = 0.32$) is much less significant, so the relationship between precipitation decline and elevation is best described in absolute terms.

Figure 6 highlights an important outlier in the data. Perisher Ski Centre, the highest elevation site, shows a decline in excess of 50 mm per year. This point is treated with a high degree of scepticism, as such values were not reproduced at any other site in the Australian alpine region. The infrastructure at the ski centre developed substantially during the analysis period, and changes in gauge location and/or instrumentation have not been ruled out. It was noted that if this gauge was excluded from the group, the decline for the other gauges decreased to a value of -36%.

In summary, a strong decline in precipitation is evident in the Snowy Mountains region on the western slopes as well as at high elevation. While the nature of the decline at lower elevations is consistent with an overall reduction in precipitation, this is not so clear for higher elevations, where the most significant relationship is between the absolute decline and elevation. This suggests that orographic factors are controlling both the enhancement of precipitation over the lower gauges, as well as the decline during the analysis period. This is supported by the fact that the near-by eastern gauges, which do not depend as much on orographic influence, have a much lower rate of decline.

In terms of snowpack depth and catchment inflows, it is the absolute decline that is of most interest. The Snowy Mountains catchments rely heavily on high elevation precipitation, and as a result have been badly affected by the precipitation declines. The remainder of this paper explores the synoptic climatology in the context of the precipitation record, and the decline, presented here.

3. Classification of precipitation by synoptic type

The water catchments in the Snowy Mountains region are fed primarily from snowmelt following the accumulation of winter precipitation at high elevations, and have been particularly badly affected by this decline. The availability of new precipitation data in this hydrologically important area for South-Eastern Australia provides a context to examine synoptic factors which affect precipitation on a day-to-day basis.

Wintertime precipitation in South-Eastern Australia is essentially dominated by mid-latitude systems that form as a result of baroclinic instability (Ryan and Wilson 1985). Some features that are commonly associated with these systems are surface and upper level depressions in pressure/geopotential fields, troughs in 1000–500 hPa thickness, and cold fronts. All of these features have served as the basis for synoptic climatologies of South-Eastern Australia in the past (Wright 1989, Pook et al., 2006, Landvogt et al. 2008).

A confounding aspect of such synoptic climatologies is that systems may at times show aspects of different synoptic types, or one type may develop into another, even when as few as two primary categories are considered. For instance, cold fronts are conceptually associated with a circulatory system, even if cyclonic flow is not apparent. Conversely, the criteria for cut-off lows in the climatology of Pook et al. (2006) do not preclude the existence of a cold front in association with the circulatory system.

There is merit, however, in classifying systems simply by the location of the parent low. Both the proximity to and intensity of the depression centre have a controlling influence over the precipitation recorded at a given location. A climatology of southern hemisphere cyclone density (number of cyclones per degree latitude squared) has been performed by Simmonds and Keay (2000), using the NCEP reanalysis data for the 40-year period between 1958 and 1997. During winter (June–August) a “split” is apparent in the Great Australian Bight region (the large open bay to the south of the continent), where few cyclones are found between 45° and 55° S, and higher numbers are found to the north and south. The 45° S parallel is a convenient natural boundary to discern between systems “cut-off” from and “embedded” in the westerly belt.

a. Precipitation events and synoptic data

The average daily precipitation record for the high elevation gauges was used in combination with synoptic data to identify “precipitation events”, which were defined as being one or more consecutive days of precipitation with an average daily value of at least 0.2 mm, and a total of at least 1.0 mm, under the influence of a single synoptic feature. The precipitation events were classified with the use of mean sea level pressure/1000–500 hPa thickness, 500 hPa height data and satellite imagery from the following sources:

- The Australian BOM synoptic charts,
- NCEP-NCAR climate reanalysis dataset (Reanalysis-II) gridded data,

- GMS/GOES/MTSAT geostationay infra red imagery.

The BOM manual MSLP analyses are publicly available from 2000, and the upper level charts from 2004. For the preceding years (1990-1999), MSLP/thickness and 500 hPa height charts were plotted from the NCEP reanalysis data. The manual analyses were used in preference to the automatically generated images where possible, since there are a number of additional observations, such as wind direction and satellite-derived cloud fields, which are incorporated into these charts. Satellite imagery was used explicitly to identify frontal cloud bands in determining whether a frontal passage had occurred, especially when the manual analyses were unavailable. Cross validation using the NCEP reanalysis data and satellite imagery for the years 2001, 2003 and 2004 showed no systematic differences in the classification decisions.

b. Classification scheme

Figure 7 shows the main categories used in this classification, which were "cut-off lows" and "embedded lows", with an "other" category included to account for the precipitation events which could not readily be attributed to either of the primary categories. This approach recognises that cold fronts are a common feature of both "cut-off" and "embedded" lows, and specifically records whether a frontal passage (as diagnosed by the path of the frontal cloud band and the geopotential thickness gradient) occurs for both types of system. The authors recognise the difficulties of defining the precise location of the front, especially with regard to passages over complex terrain, and the statistics generated from this definition have been used with caution.

The classification scheme ultimately resembles the scheme used by Pook et al. (2006) quite closely, except for a longitudinal shift in the analysis region and the replacement of the "cold front" category with the more general "embedded low" category. Cold fronts are analysed as an additional feature which may or may not be present (i.e. "frontal"/"non-frontal") in both of the major synoptic types.

(i) Cut-Off Lows

Wintertime cyclones propagating over the Great Australian Bight may make landfall over the Victorian coast, pass through the Bass Strait or divert over or to the south of Tasmania. All of these storm paths may be associated with significant precipitation on the mainland. The systems are generally associated with a cold anomaly aloft that is "cut-off" from the Southern Ocean westerly belt (figure 8). Precipitation during an event was attributed to a cut-off low if a minimum in either the MSLP or the 500 hPa geopotential field was present east of 135° E, west of 150°, E and north of 45° S. The circulation around these minima was not required to be closed. Complex systems (with more than one pressure minimum) were only classified as "cut-off" if the major centre of circulation fell within the prescribed region.

(ii) Embedded Lows

The circumpolar storm track in the Southern Ocean is a region of high cyclone density, located year-round to the south of 50° S (Trenberth 1991). Though distant from South-Eastern Australia, cyclones "embedded" in this westerly belt can have a strong influence over weather in the Snowy Mountains, as the frontal bands and large amplitude troughs associated with these systems can extend for more than a thousand kilometres across the Southern Ocean. Precipitation during an event was attributed to an embedded low if it occurred during the passage of a front or trough that could be linked to a cyclone or wave in the westerly belt.

(iii) Cold Fronts

Meteorological fronts are characterised by a moving boundary which marks a region of sharp transition in thermodynamic properties between different airmasses. In particular, a cold front moves so that colder, denser air replaces warmer air. Forced uplift of the warmer air in this process result in patterns of precipitation that can be related to finer details of the frontal structure (Browning 1986). Of particular importance to precipitation in mountainous regions is the “warm conveyor” (more recently termed “atmospheric rivers” by Zhu and Newell (1994)) mechanism, where a narrow, low-level jet within the boundary layer just ahead of the surface cold front carries large quantities of moisture poleward. Cold fronts are always associated (at least in a system-relative sense) with cyclonic circulation, and are commonly found in association with both of the above categories.

(iv) Other systems

Although the two major systems were found to account for nearly 90% of precipitation events, a number of events in most years were attributed to “other” systems. In particular, it was found that easterly conditions seldom brought substantial precipitation, as they tended to rain out on the rugged coastal ranges.

- *East Coast Lows* (Holland et al. 1987), are potentially destructive, heavily precipitating systems that typically develop from upper level disturbances over the enhanced sea surface temperature gradients near the east coast of the continent.

- *Easterly dips* are characterised by a weak trough along the east coast of the continent. They are a regularly occurring phenomenon in Australian meteorology and signify a tropical-subtropical interaction. These systems are a common precursor for the formation of east coast lows, and are more commonly associated with summertime precipitation in the region.

- *Indeterminate precipitation events* are unable to be associated with any synoptic-scale features. Small-scale convective events may account for considerable precipitation amounts at one or more gauges.

- *Erroneous precipitation recordings* can occur due to a number of reasons, including blowing snow, heavy dew/frost or equipment malfunction.

c. *Climatological features for the period 1990–2009*

A total of 623 precipitation events were classified according to the above scheme. Summary results are shown in table 2, where the mutually exclusive categories of "embedded low" and "cut-off low" are further subdivided into "frontal" and "non-frontal". The combined "frontal" and "non-frontal" events are also shown. The median and quartile values of precipitation per event are also given in table 2.

1) Statistics for entire analysis period

Embedded lows account for 47% of all precipitation events, occurring slightly more frequently than cut-off lows (43%). However, embedded lows bring considerably less precipitation on a seasonal basis, accounting for about 40% of precipitation compared to 56% for cut-off lows. Precipitation generally persists for longer during a cut-off low (2.7 days) than for an embedded low (1.9 days).

Cold frontal passages in the Snowy Mountains, as diagnosed by the position of the frontal cloud band and the geopotential thickness gradient, account for around 79% of all precipitation in the winter months. They are slightly more frequent for cut-off lows (occurring in 70% of cases) than for embedded lows (62% of cases). The proximity of the parent low to the region clearly plays an important role in this statistic, with numerous "near misses" as a cold front associated with an embedded low slips southward of the mountainous regions. Cut-off lows without a cold frontal passage near the Snowy Mountains are usually either in a decaying phase, or pass to the north of the region, but may still bring considerable precipitation.

Total precipitation per event is shown in probability distribution histograms in figure 9. The distributions are similar to log-normal distributions, which are shown by diamonds for distributions of the same mean and standard deviation as the precipitation totals. Negative skewness is especially evident in the distribution for frontal types, indicating that precipitation heavier than the mean amount is more important to the winter totals than light precipitation.

Cut-off lows tend to bring the heaviest precipitation, with one in four bringing more than

50 mm and one in ten bringing more than 100 mm. A cold frontal passage has significant impact on both the intensity and duration of precipitation. The median precipitation amount during a frontal passage is about 32 mm over 2.5 days, compared to 8.9 mm over 1.85 days for precipitation events in which a frontal passage does not occur.

d. Annual variability and trends

Year-to-year variations in the frequency of precipitation events and the total amount of precipitation brought by these are shown in figure 10 (Pook et al. 2006, c.f. figure 8). The attribution of precipitation to the two major synoptic types is reasonably consistent throughout the analysis period. More cut-off lows were diagnosed than embedded lows in eleven of the twenty years, and cut-off lows brought more precipitation in all but four years.

The number of precipitation events clearly plays a role in the amount of precipitation brought in a given year; of the three years with the least number of precipitation events, two of these (1994 and 2006) are the driest years on record. The correlation between the number of systems and the total wintertime precipitation is moderate ($r = 0.51$), but there is a weakly positive trend (not statistically significant) in the number of precipitation events per season, so the hypothesis that the declining trend in precipitation is caused by less frequent storms must be rejected.

The magnitude of the downward trend in total winter precipitation (discussed in the previous section) is the sum of the decline for both of the major synoptic types. The decline in precipitation due to cut off lows was found to be 18.1 mm per year, which in relative terms is about twice the value of the decline due to embedded lows. Only the decline in precipitation due to cut-off lows was statistically significant.

No trend in the frequency of cut-off lows was identified in the analysis, so it may be inferred that the amount of precipitation per event must have decreased to make up the decline. A slight, non-significant decline in the number of rain days per event was noted for both cut-off and embedded lows (-0.4 and -0.1 cut-off rain days per year respectively), but the amount of precipitation per rain day (a measure of intensity) was noted to have declined by 0.34 and 0.20, significant at the 1% level. These results clearly indicate that precipitation intensity has declined in the Snowy Mountains region, especially so for cut-off lows.

The same decomposition has been performed for the average daily precipitation from the network of 38 gauges on the lower western slopes, where a similar pattern was seen. For both synoptic types, the ratio of low-elevation to high-elevation decline was very close to 2.7; that is, the relationship between elevation and overall precipitation decline does not appear to depend on the synoptic types investigated.

The frequency of occurrence of frontal types was found to have decreased by 0.17 per year, amounting to a decline in 18% over the analysis period. It may be that frontal systems have slipped further to the south over the past two decades and passages are occurring less frequently in the mountainous regions, resulting in less intense and prolonged precipitation. This is consistent with the trend in the SAM index towards more frequent positive values, but the lack of statistical significance and the uncertainty of this parameter make it difficult to make a strong conclusion.

4. Climatology of back trajectories in the Snowy Mountains region

Meteorological trajectories represent the path of an infinitesimally small parcel of air by advection due to large scale winds, and are typically calculated by integration of wind fields from archived meteorological data. They are a useful representation of the airmass history at the point of termination and may be used to identify moisture sources during precipitation events. Trajectory calculations for this analysis were performed using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) modelling system (Draxler and Hess 1998). The meteorological data used was the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-analysis (ERA-Interim) data (Simmonds et al. 2007), projected onto a 180 × 180 polar stereographic grid and processed into a format suitable for ingestion into HYSPLIT.

a. Airmass history during wintertime

Moisture is transported by advection in all levels of the troposphere, but water vapour mixing ratios tend to be highest near the surface, implying that the bulk of moisture is transported in the lower levels. Trajectories arriving at a set of levels below 5000 m AGL (above ground level) above Mt Blue Calf (148.39° E, 36.39° S; a central mountaintop location) were calculated on three-hourly intervals for the months of May–September in the period 1990–2009.

Trajectories arriving at 500 m AGL are presented for analysis as these are particularly relevant for orographic clouds. The hourly position of air parcels on 24480 trajectories were binned at 0.5° resolution in latitude and longitude, giving a position probability distribution (PPD), which represents the relative *contribution* of a given location to the airmass history of air arriving in the Snowy Mountains. This distribution is displayed in figure 11 (final panel).

The shape of the distribution is axially non-symmetric, with the majority of trajectories arriving from the south-west. A secondary path for trajectories from the north appears to be evident over central New South Wales, roughly following the contours of the Great Dividing Range.

b. Sources of moisture during precipitation events

In order to identify moisture corridors and sources, trajectories arriving at 500 m were selected if precipitation recorded by the SHL gauges during the three hours prior to arrival was more than a threshold amount. Figure 11 shows the differences between the PPD for trajectories selected at thresholds of 0.2 mm (trace), 1.0 mm (light), 3.0 mm (moderate), and the trajectory climatology.

Precipitation is more frequently associated with trajectories that pass through the blue shaded regions. The features that are present for all precipitation thresholds are an enhancement for trajectories arriving from the west-north-west (a primary moisture corridor), and suppression for anything arriving from the half-circle between north-east to south-west. These effects are accentuated for higher precipitation thresholds.

The west-north-west corridor is roughly perpendicular to the topography in the Snowy

Mountains, suggesting orographic enhancement of precipitation under these flow conditions. Some evapotranspiration might be expected over the land surface over north-western Victoria in this direction, but boundary layer moisture was most likely to be transported from the Great Australian Bight region. Higher level trajectories (not shown) were generally found to transport moisture from this sector, with trajectories above 3000 m frequently transporting moisture from the warm seas to the north-west of the continent, consistent with satellite observations of "north-west cloud bands" which display this process (Tapp and Barrell 1984).

A second corridor to the north demonstrates that moisture from the north-east is being transported to the Snowy Mountains. This feature is especially pronounced for more intense precipitation, and for precipitation amounts above 15 mm (recorded over three hours) this corridor completely dominates. It is a hallmark of the warm conveyor mechanism (Browning 1986), or atmospheric river (Zhu and Newell 1994) ahead of a cold front. The topography of the Great Dividing Range appears to play a role, presumably acting as a barrier to low-level westerly flow.

Combined, the two corridors characterise the change in airmass over the course of a strong frontal passage. Inland transport of moisture from the warm, north-eastern Coral Sea (north of 30° S), by onshore easterlies in the subtropics (apparent in the composites in figure 8), is followed by southward transport by the warm conveyor. When this narrow belt of warmer, moist air meets the Snowy Mountains, precipitation may be moderate to heavy, but generally not long lived. More frequent, lighter precipitation is associated with trajectories arriving from the west corresponding to the change in airmass following the frontal passage.

The region shaded red to the south and south-west is identified as being much less important as a moisture source for the Snowy Mountains region. Trajectories passing over this region are less likely to be associated with any precipitation amount. This means that either the synoptic systems responsible for bringing precipitation do not result in trajectories from the south-west, or there is some mechanism suppressing precipitation in this region. Figure 11 shows that the suppressed region is to the far side of the Victorian Alps, which are apparently casting a rain shadow over the Snowy Mountains during south-westerly conditions. Indeed, a similar pattern is observed when the same analysis is performed for a number of high-elevation AWS sites along the north-western slopes of the Great Dividing Range, between Mt Ginini to the north and Mt Buller in the southern Victorian Alps (these are located within the analysis region in figure 1). When performed for the Mt Baw-Baw AWS (to the south of the divide), the PPD shows a complementary pattern of suppression from the north-west and enhancement from the south-east. This indicates that either different phases of storms or different synoptic systems altogether are responsible for precipitation in alpine regions with a southern aspect.

c. Atmospheric circulation, trajectories and precipitation

Meteorological trajectories naturally reflect changes in regional circulation. For the southern Australian region, the Southern Annular Mode is of particular importance and has been shown to be associated with cool season precipitation (Nicholls 2010). In figure 12, trajectory composites have been formed by selection of trajectories based on the sign of the monthly SAM index. For the negative phase, which describes an equatorward shift of the westerly belt, precipitation is shown to be more regularly associated with trajectories which have come from the west, with no remarkable contribution from the northern corridor. For the positive phase, the northern corridor is relatively much more important. Precipitation amounts above 1.0 mm are more frequent in the negative phase of the SAM, with 21% of all trajectories bringing at least this amount, compared to 15% for the positive phase. Incidentally, precipitation amounts for the high elevation gauges in the months with a negative SAM index were found to be about 30% higher than for months with a positive value.

A conceptual interpretation of these different patterns is that for negative values of the SAM index, there is a stronger influence of post-frontal flow over the topographic barrier. For positive values, the westerly stream brings less frequent precipitation, and the conveyor mechanism (frontal precipitation) plays a more dominant role.

This result gives insight into the exacerbated decline in precipitation amounts on the western slopes and at high elevation in the Snowy Mountains region. Trends in the wintertime SAM index during the analysis period have been strong, with about 1.5 more positive *monthly* values per year recorded at the end of the analysis period compared to the start. This represents a change in global circulation corresponding to a poleward shift in the average position of the westerly belt. Decreased westerlies over the Snowy Mountains region would result in a decrease in the orographic enhancement of precipitation, which is most important for the exposed slopes and high elevation regions. This is wholly consistent with Budin (1985), who found that years with stronger low-level westerlies are significantly related to winter snowpack depth.

Trajectories were also sorted on a range of different bases. Selection based on sign of the Southern Oscillation Index resulted in no substantial differences from the composites in figure 11, suggesting that this index does not impact trajectories associated with precipitation in the Snowy Mountains. When selected on the basis of synoptic type, the differences were quite subtle, the main feature being the increased relative importance of the westerly corridor for embedded lows. Selection of trajectories based on whether they came from one of the five wettest or driest years resulted in composites that were very similar to those in figure 12, as would be expected if the phase of the SAM index plays a role in the seasonal precipitation amount.

5. Discussion and Summary

Precipitation in the alpine regions is important to the economy and ecology of South-Eastern Australia, with enhanced wintertime orographic precipitation in the high elevation regions resulting in twice the precipitation amount of the lower slopes, and four to six times the amount for the western plains of the Murray-Darling Basin. The wintertime (May–September) precipitation decline in the period 1990–2009 is especially evident in the high elevation regions, with an average decline of about 43%, amounting to a precipitation deficit in the order of 500 mm per year. This is by far in excess of the average declines in South-Eastern Australia over the same period and has had a high impact on catchment inflows and snowpack depths over the past decade.

Given the contrast between the decline between the eastern and high elevation/western gauges, as well as for the more general decline in South-Eastern Australian precipitation, it is tempting to attribute the exacerbated decline to factors affecting orographic precipitation. After all, the western slopes gauges have a relatively high average elevation (645 m) and are exposed to the prevailing westerlies, so orographic factors mast be important here.

While it has been established that orographic precipitation may be affected by aerosol pollution (Rosenfeld 2000) (indeed this factor has been invoked in discussions into Snowy Mountains precipitation amounts), whether this could result in a hydrologically important impact is unresolved. Instead, this paper considers changes in the amount of precipitation attributed to manually identified synoptic types and back trajectory analysis.

Wintertime precipitation in the Snowy Mountains was decomposed into two major categories:

- Cut-off lows with minima in MSLP or 500 hPa height located north of 45° S, accounting for 56% of total precipitation, and 43% of all precipitation events.

- Embedded lows, in the circumpolar westerly belt south of 45° S, accounting for 40% of total precipitation and 47% of all precipitation events.

About 59% of precipitation events (accounting for 79% of precipitation) were associated with a cold frontal passage over the region. Over the twenty year period, embedded lows were more frequent than cut-off lows in all months except July, but cut-off lows brought more precipitation than embedded lows in every month except August.

Pook et al. (2006) noted that the statistic of rainfall per station per cut-off day declined over their period of analysis, and this climatology both confirms and extends this result to the present date. The decline in wintertime precipitation over the 20 year analysis period was found to be about 40%, and this was mostly apparent in precipitation intensity, especially from cut-off lows. Although there are no trends in the frequency of either embedded or cut-off lows, the number of precipitating systems associated with a frontal passage was estimated to have declined by about 18%. Both of these results are consistent with the hypothesis that observed trends in intensity of the subtropical ridge (Larsen and Nicholls

2009) or Southern Annular Mode (Nicholls 2010) can cause changes in the paths followed by mid-latitude storms.

Back trajectories provide useful insight into synoptic transport of moisture for precipitation. The climatology of low-level trajectories arriving in the alpine regions of the Snowy Mountains highlights the following key features:

- Moisture during wintertime precipitation arrives at low levels via two principal routes: a direct west-north-west corridor and a circuitous northerly corridor. Both of these corridors become more pronounced for higher precipitation rates.

- Enhancement of precipitation from the west-north-west is principally linked to orography, as this flow is aligned with the terrain gradient.

- The Southern Annular Mode plays an important role in the pattern of trajectories associated with precipitation. Negative (positive) phases of the SAM show a greater (reduced) contribution of the westerly stream to precipitation amounts.

- Enhancement of precipitation for trajectories arriving from the north is linked to moisture transport from the north-eastern subtropical sea surface by the warm conveyor mechanism associated with cold fronts.

Although seasonal South-Eastern Australian precipitation amounts are closely related to alpine precipitation, explanations for the decline in South-Eastern Australian precipitation based on climate indices (Timbal 2009, Nicholls 2010) or sea level pressure (Larsen and Nicholls 2009) do not explicitly account for the exacerbated decline at high elevations. It might be inferred that decreases in the westerlies due to a poleward shift in the storm tracks would lead to decreased precipitation, especially where the role of orography is important, and this is indeed supported by observations of snowpack depth (Budin 1985). The position probability distributions of trajectories presented here provide an important physical link between the SAM index and orographic precipitation.

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Site	Lon.	Lat.	Elev.	An. Pr.	An. %	M-S %	Avail.
The Kerries	148.38	-36.26	1740	1358	80	72	1995
Jagungal	148.39	-36.14	1659	1705	92	97	1990
Guthega Dam	148.37	-36.38	1558	1457	90	92	1994
Tooma Dam	148.28	-36.05	1221	1775	96	91	1992
Island Bend	148.48	-36.31	1221	1061	90	89	1995
Geehi Dam	148.31	-36.30	1175	1656	96	96	1992
Perisher Ski Centre*	148.41	-36.40	1735	*1696*	75	88	1976
Thredbo Village*	148.30	-36.50	1380	*1684*	89	78	1971
Guthega P.S. †	148.41	-36.35	1320	1479	88	87	1952
Cabramurra †	148.38	-35.94	1482	1373	97	97	1955
Khancoban‡	148.14	-36.23	328	863	98	99	1993
Jindabyne§	148.61	-36.42	927	587	94	93	1992
Eucumbene§	148.62	-36.13	1180	793	86	84	1992

TABLE 1. The precipitation gauges introduced for this analysis. The first group are the nine gauges that form the "High Elevation" group, including six SHL gauges, two manual BOM gauges (*) and the two merged manual/automatic datasets (†). The SHL Khancoban gauge (‡) is added to the network of 37 BOM gauges on the lower western slopes, and the remaining SHL gauges (§) are included with 19 BOM gauges to the east of the ranges. Annual Precipitation, percentage of daily precipitation available (annual and May–September) and year of commission are also shown. Values in italics are not quality controlled in any way and are calculated from monthly accumulations available on the Australian Bureau of Meteorology website.

	No. Events	Total Precip.		Rain Days	Precip. per Event		
	per yr.	*per yr.*	*%*	*per yr.*	Q_1	$\tilde{x}$	Q_3
All types	31.1	916.3	(100.0%)	69.0	8.1	20.5	42.4
E. Lows	14.6	364.8	(39.8%)	28.2	6.5	17.2	34.7
E. Lows w. front	9.0	317.9	(34.7%)	20.2	16.0	27.2	49.6
E. Lows w/out front	5.5	46.9	(5.1%)	8.0	3.1	6.0	13.3
C.O. Lows	13.3	510.9	(55.8%)	35.3	14.9	31.3	52.9
C.O. Lows w. front	9.3	407.9	(44.5%)	25.4	17.8	34.9	59.2
C.O. Lows w/out front	4.0	103.0	(11.2%)	9.8	8.6	19.4	33.1
All w. front	18.4	725.8	(79.2%)	45.7	17.1	31.9	54.4
All w/out Front	9.6	149.9	(16.4%)	17.8	4.1	8.9	20.0
Other	3.2	40.6	(4.4%)	5.5	2.5	6.1	14.8

TABLE 2. Summary of statistics from the synoptic decomposition of wintertime precipitation in the Snowy Mountains region during 1990–2009. The mutually exclusive categories of "embedded low" and "cut-off low" are further subdivided into "frontal" and "non-frontal", and the combined "frontal" and "non-frontal" events are also shown. Here, Q_1 and Q_3 represent the first and third quartiles, and $\tilde{x}$ is the median value of precipitation per event.

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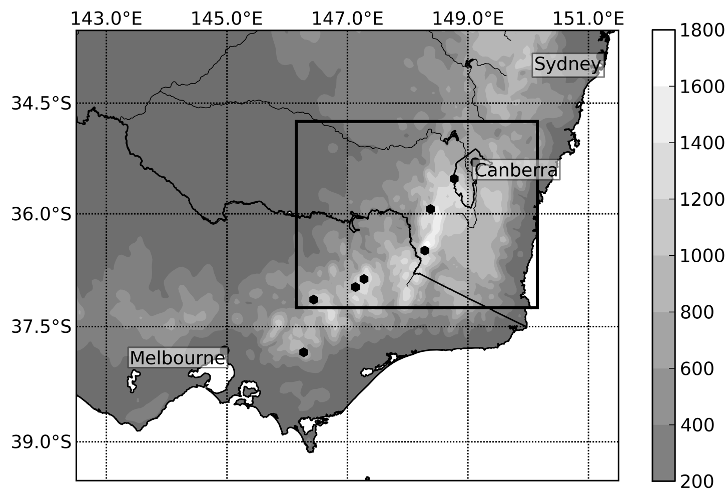

FIG. 1. Topography of South-Eastern Australia, showing Great Dividing Range and locations of Australian Bureau of Meteorology automatic weather stations in alpine conditions. The rectangular outline marks the analysis region.

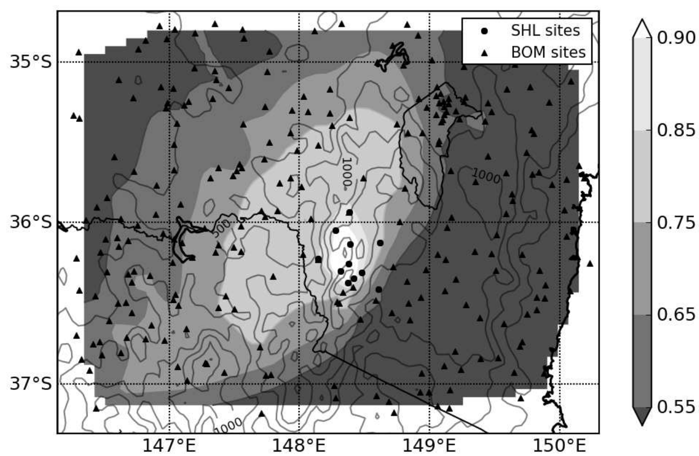

FIG. 2. All precipitation gauges in the Snowy Mountains region in operation during the analysis period. Filled contours show correlation coefficient with the *alpine daily average* precipitation calculated from the high-elevation SHL gauges. Contours of topographic elevation shown at intervals of 250 m, with the highest contour shown at 1500 m.

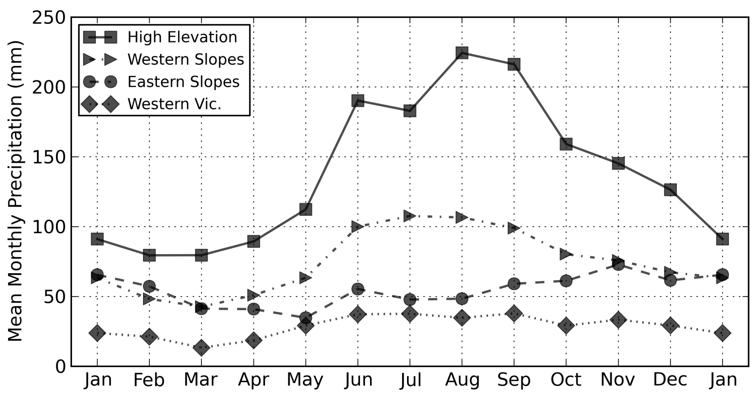

FIG. 3. Monthly precipitation averages for groups of Snowy Mountains region gauges (see text) for the years 1990-2009. Included for comparison are the means for the western Victoria gauges used in the climatology of Pook et al. (2006), for the same period (except for Bendigo Prison station, which closed in 1992).

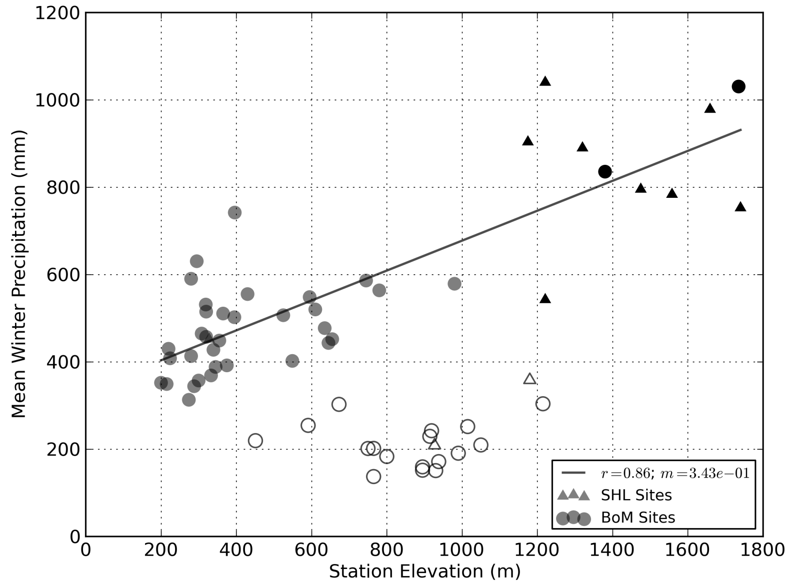

FIG. 4. Mean winter precipitation plotted against station elevation for all gauges. Eastern slopes gauges are plotted with open symbols, western slopes in light shade and high elevation groups in dark shade, with different symbols used for gauges from the two networks. Eastern slopes gauges are not used in regression.

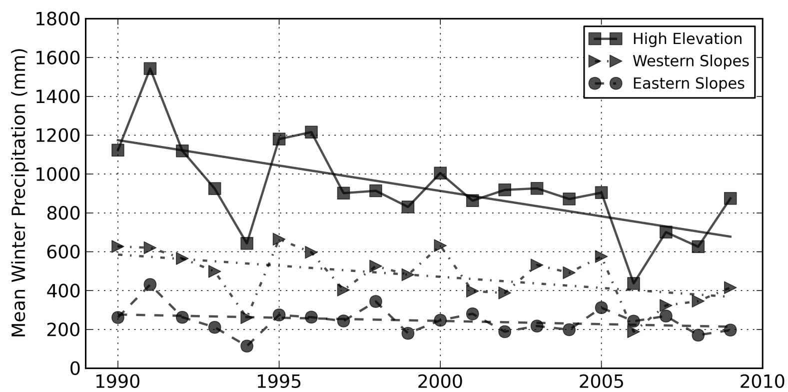

FIG. 5. May–September precipitation averages for the Snowy Mountains gauge groups. The linear fits have slopes of −23.18, −11.44 and −3.30 respectively. Trends for the high elevation and western slopes are statistically significant with $P < 0.02$.

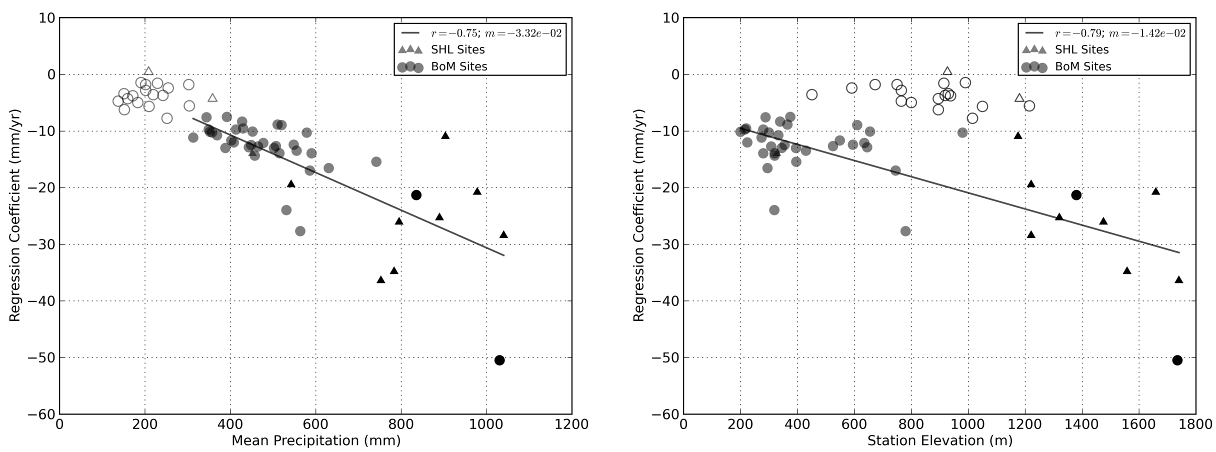

FIG. 6. Regression coefficient for 20 year trend plotted against mean wintertime precipitation (left), and station elevation (right). Symbols and regressions as for figure 4.

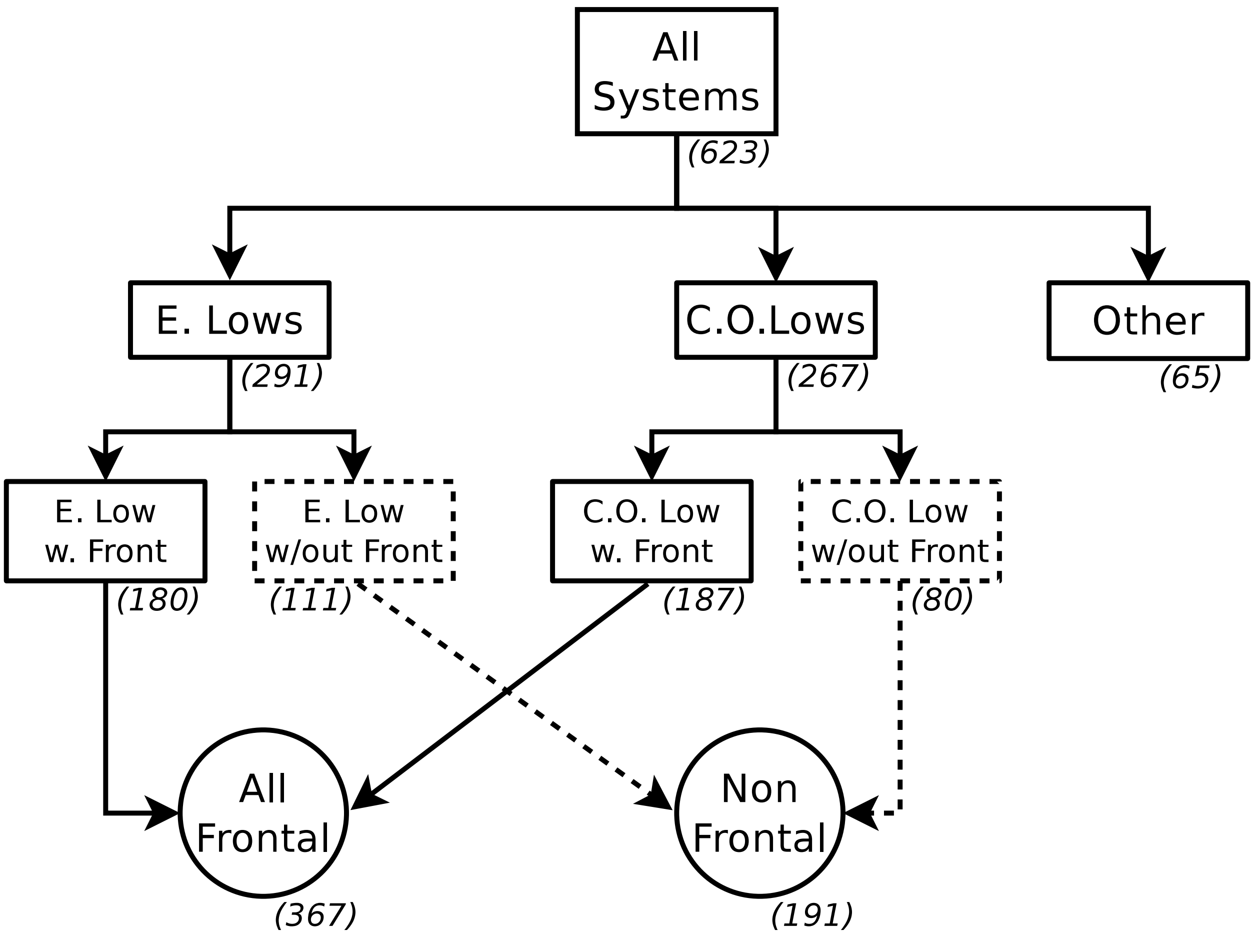

FIG. 7. Schematic of classification procedure, including total number of each event type classified for winter months in the period 1990–2009.

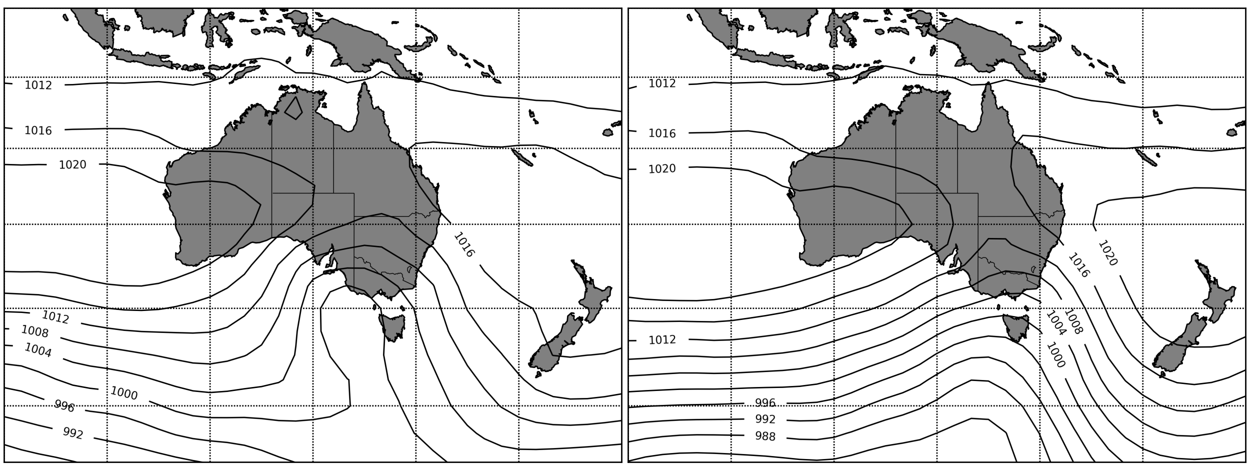

Fig. 8. Composites of the mean sea level pressure for the 20 cut-off lows (left) and 20 embedded lows (right) bringing the most precipitation to the Snowy Mountains. The intensity of the composite cut-off low is somewhat understated due to the variability of its position in the NCEP re-analyses.

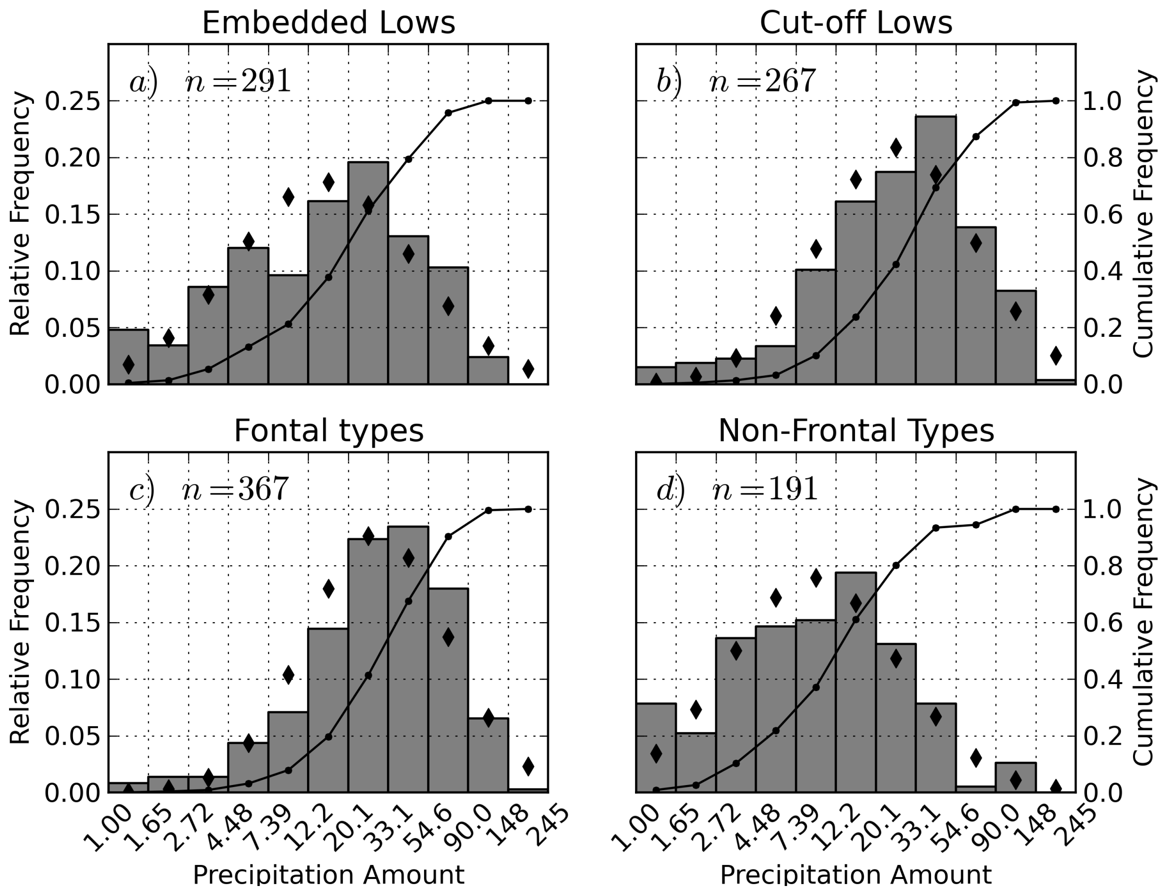

Fig. 9. Probability histogram of precipitation amount (note logarithmically spaced bins), for the major synoptic types. The sigmoid shows the cumulative contribution of the bins, and the diamonds depict the log-normal distribution corresponding to the mean and standard deviation of precipitation amount.

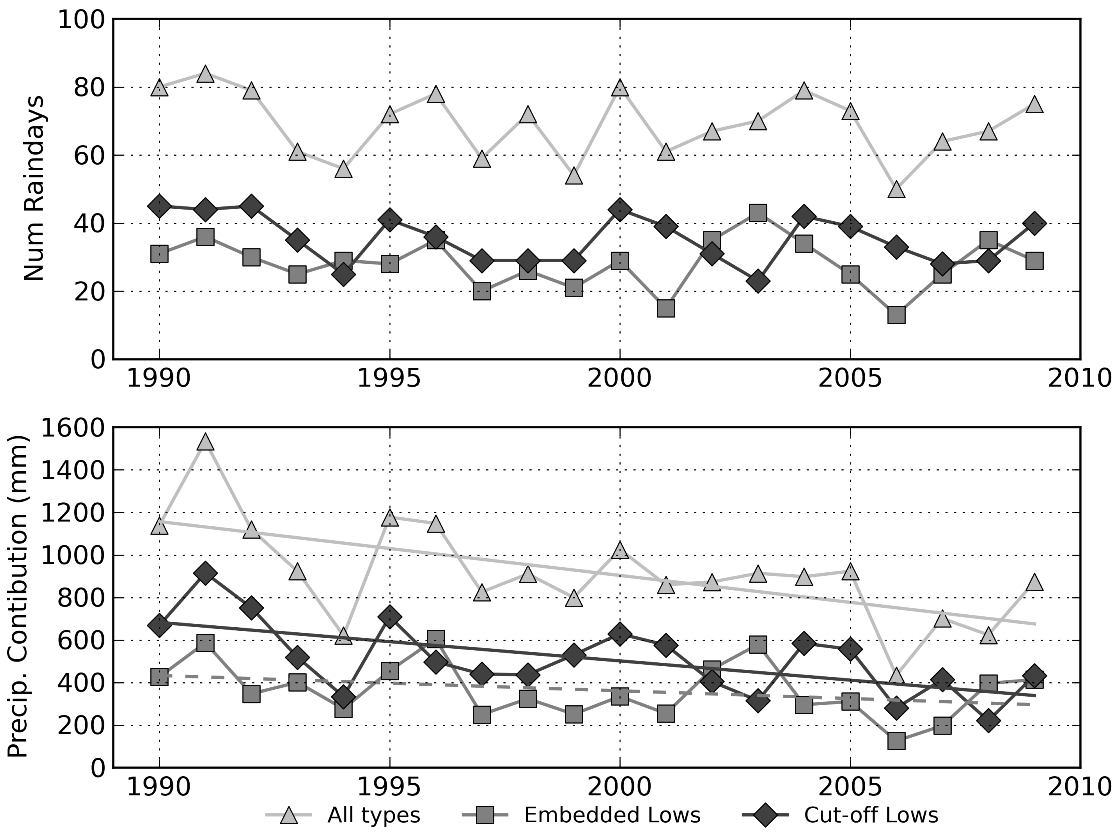

Fig. 10. Number of occurrences (above) and contribution to wintertime precipitation amount (below) for the two major synoptic categories. Statistically significant trends are shown with solid lines.

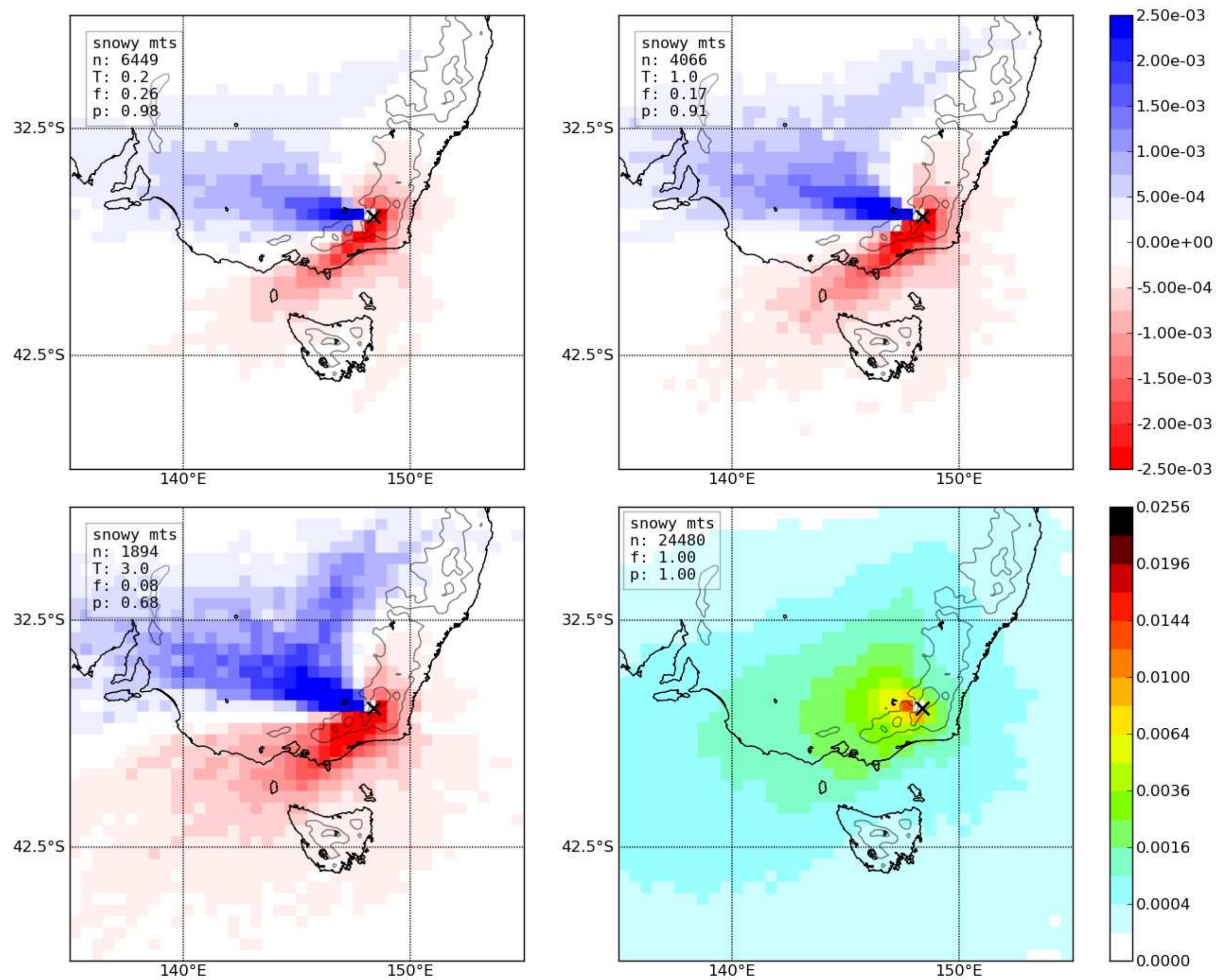

FIG. 11. Difference in position probability distribution for all trajectories, and those associated with at least $T = 0.2$, 1.0 and 3.0 mm over the preceding three hours. The lower right panel shows the PPD for all trajectories. The number of trajectories used to create each composite is denoted by n, the proportion of all trajectories used to create the composite by f, and the proportion of precipitation accounted for by p. Terrain elevation is shown by contours of 500 and 1000 m.

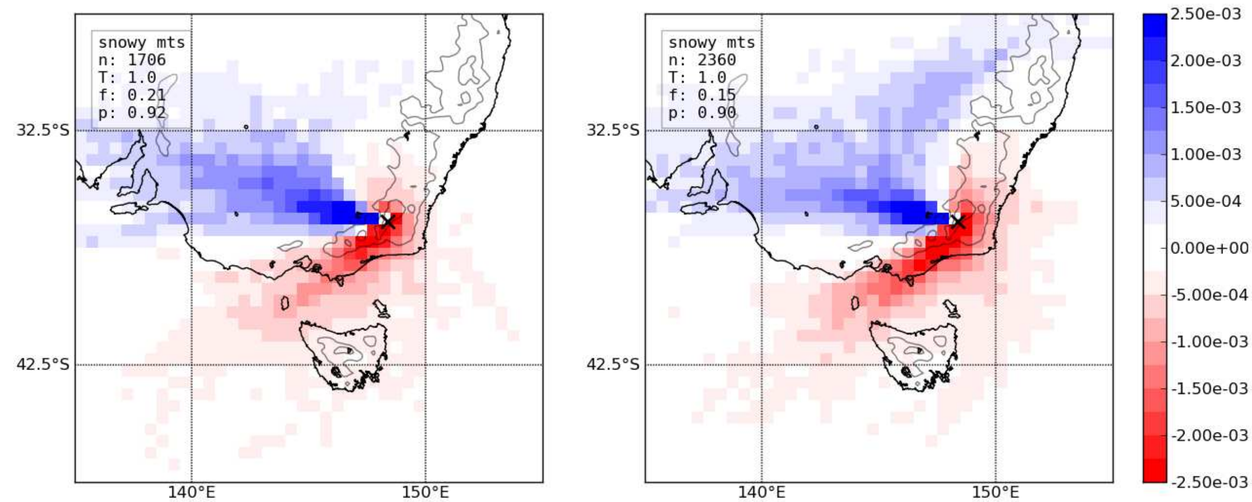

FIG. 12. As for figure 11, except for trajectories arriving in months with negative (left) and positive (right) SAM index.