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Significant decline in storminess over southeast Australia since the late 19th century

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Geostrophic wind speeds (geo-winds) were estimated for southeast Australia by constructing eight station triangles from instrumental records of quality-controlled sub-daily mean sea-level pressure from 1885 to 2008. Seasonal 95th and 99th percentiles of the geo-winds were calculated and used to identify periods of enhanced 'storminess' over each triangle. While the results were marked by strong multi-decadal variations, they indicated a statistically significant decline in storminess across most regions in southeast Australia since the end of the 19th century, particularly in autumn and winter. The results for winter for most regions were also statistically significantly correlated with year-to-year variations in southeast Australian rainfall although the correlation coefficients were small. Regionally averaged results showed a peak in storminess in the 1920s with least activity in the 1960s in all seasons. Although there has generally been an upturn in storminess in recent decades compared to the immediately preceding decades, it has not been of nearly the same magnitude as in the late 19th and early 20th century. While similar studies have been performed in the northern hemisphere over this length of period, we believe that this is the first time that the method has been applied to Australia. The results indicate that in addition to other climatic processes, the long-term decline in storminess may be contributing to the persistent drought conditions that are being experienced in this densely populated region.

Introduction

In the last decade or more, reductions in rainfall, particularly in the winter half-year (e.g. Murphy and Timbal 2008), and persistent drought conditions across densely populated regions of southern Australia, have caused concerns that factors other than natural climate variability are driving observed climatic changes. While the mechanisms for this are still the subject of much debate (Sherwood 2009), there is some evidence that changes in synoptic weather patterns have led to a decline in the frequency and/or intensity of rain-bearing or storm systems reaching southern Australia (e.g. Hope et al. 2006; Verdon-Kidd and Kiem 2008; Frederiksen et al. 2010). However, previous studies of 'storminess' have mostly relied on reanalysis data because of the lack of access to early observational data across Australia prior to the mid-20th century (Harle et al. 2008). Understanding the long-term variability of storm activity would give a much better perspective on how unusual recent climate variations have been. For southeast and eastern Australia some studies have been able to assess measures of storm activity over longer periods back to the 19th century (e.g. Alexander and Power 2009; Rakich et al. 2008), finding either a decline in the number of storms or reduction in the strength of zonal geostrophic wind flow, though in these cases results were limited to the analysis of only one or two locations. The present study we believe is the first to analyse storminess across the whole of southeast (SE) Australia using extreme geostrophic winds deduced from station triangles of pressure observations back to the late 19th century.

Extreme geostrophic wind speeds, or 'geo-winds', have been employed in a number of studies of North Atlantic and European storminess using centennial and longer time scale *in situ* observations (e.g. Schmidt and von Storch 1993; Matulla et al. 2008; Wang et al. 2009). The assumption

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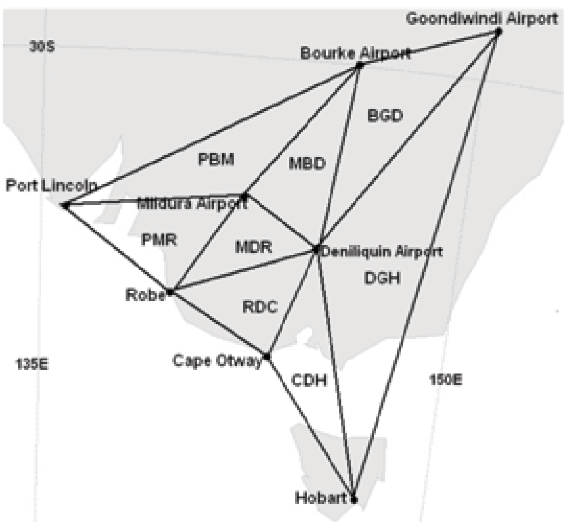
is that outside of the tropics, geo-winds form a reasonably good first approximation for actual wind speeds and provide a much more reliable and homogeneous measure than wind speed measurements which are sensitive to site moves and instrumentation changes (Wan et al. 2010). We apply this method to quality-controlled sub-daily mean sea -level pressure (MSLP) observations at eight sites across SE Australia to form eight triangular regions. These data, with the earliest observations dating back to 1859, have only recently become available following a digitization project by the Australian Bureau of Meteorology (BoM) and they are used here to reconstruct measures of historical storminess for SE Australia.

This study first discusses the observed data-set and quality-control procedures used, followed by the method employed to construct geo-winds and the calculation of 95th and 99th percentiles of these geo-winds to represent measures of storminess. Finally, we analyse the long-term variability and trends in storminess over this region and show how or if they are linked to large-scale circulation modes and rainfall variability in the region.

Data and methods

Sub-daily MSLP data were obtained from BoM and are a subset of data described in Alexander et al. (2010). The locations of the sites and associated station triangles analysed in this study are shown in Fig. 1. Table 1 also gives more information about each station location, including the start dates of available observations. Data were obtained for each site up until the end of February 2009 in order to include the complete 2008–09 summer (DJF) season. In some cases, where a station has closed or moved, a substitute station was found and the observations combined into one series. The quality of the data was tested by analysing pressure tendencies (i.e. the difference between two subsequent MSLP observations) both within and between stations to highlight unusually large values. A total of 60 potentially erroneous values were identified using this method and these were either set to missing or corrected where possible.

Fig. 1 Stations used in this study with associated triangles for calculating geostrophic wind speeds.



In addition to quality, the consistency of the MSLP time series is of the utmost importance in order to adequately analyse long-term variability and trends. The homogeneity of these series was tested using the method of Wang (2008) and any mean shifts detected to be significant at five per cent level were adjusted accordingly. Three of the stations (Port Lincoln, Robe and Hobart) did not require any adjustment, one station (Deniliquin) had one detectable mean shift, two stations (Goondiwindi and Bourke) had two mean shifts and the remaining two stations (Mildura and Cape Otway) had three mean shifts. Most of these change points were detected in the early part of each station record. While a number of factors can influence the homogeneity of MSLP data, two important ones are the methods used to convert station pressure to MSLP, and the station elevations used in those conversions. There have been a number of changes over time in the pressure conversion methods used (Seaman, 1997), but as all of the stations in this study are at elevations below 220 metres (Table 1), these changes are of limited importance. More significant have been changes in the surveyed elevation of stations; in the early years it was relatively common for a resurvey to change a station's listed elevation without any physical move of the instruments. As an elevation change of 10 m changes station pressure by approximately 1 hPa, a modest resurvey can have a substantial effect on MSLP data. In the absence of detailed information, it is reasonable to assume for the purposes of this study that any large impacts on MSLP over time as a result of resurveying will be identified by the homogeneity testing.

After ensuring the quality and homogeneity of these sub-daily MSLP time series, geo-winds were derived from these data and used to assess historical trends and variability of storminess in SE Australia. A detailed description of the method used is given by Wang et al. (2009), but in short instantaneous geo-wind speed, W_g, is calculated from meridional (u) and zonal (v) wind-inferred components such that:

$$w_g = \left(u_g^2 + v_g^2\right)^{1/2} \qquad \ldots 1$$

where u and v are functions of air density, the Coriolis parameter and the zonal and meridional pressure gradients respectively of the instantaneous MSLP values at the three locations making up the station triangle.

Observation times varied with many stations recording hourly or three-hourly but mostly only in the last few decades. All stations used in this study have observations

[1]In most cases observations are taken at the same local time all year, so are effectively one hour earlier in standard time or UTC when daylight saving time is in use.

Table 1. The eight sites and the related stations of mean sea-level pressure (MSLP) data analysed in this study. Where two time zones are listed, the second refers to daylight saving time periods (in general, November–March since the early 1970s) and the first to the remainder of the year. Elevations are of the site in current use.

Site	*Name of station(s)*	*Station IDs*	*Start date*	*Elevation (m)*	*Time zone (2009)*
Rob	Robe	026026	Sep 1884	4	UTC + 9.5/10.5
Cap	Cape Otway	090015	Jan 1861	83	UTC + 10/11
Hob	Hobart	094029	May 1893	51	UTC + 10/11
Por	Port Lincoln; Port Lincoln AWS	018070; 018192	Jan 1892	9	UTC + 9.5/10.5
Den	Deniliquin; Deniliquin Airport AWS	074128; 074258	Sep 1859	95	UTC + 10/11
Mil	Mildura Post Office; Mildura Airport	076077; 076031	Feb 1891	53	UTC + 10/11
Bou	Bourke; Bourke Airport; Bourke Airport AWS	048013; 048239; 048245	Mar 1892	108	UTC + 10/11
Goo	Goondiwindi; Goondiwindi Airport	041038; 041521	Mar 1891	219	UTC + 10

at, or near, 0900 and 1500 local time[1] for most or all of the periods of record. For the purpose of sampling homogeneity, we used the geo-wind series derived from these two observation times throughout the period analysed in this study. There have been some historical variations in observation timings (current time zones are shown in Table 1); for example, daylight savings time was not observed (with a few exceptions) prior to the early 1970s, in the 1940s and early 1950s the South Australian stations (Robe and Port Lincoln) did their observations according to a UTC + 10 schedule, and prior to 1939 observations were done using local solar time, not standard time. However, the net result is that, in virtually all cases[2], the three observations defining each triangle were taken within 60 minutes of each other. The PMFred homogenization technique of Wang (2008) was applied to the monthly mean geo-wind series to double-check their temporal homogeneity. All these series were found to be homogeneous at 95 per cent level of confidence.

The sub-daily geo-wind values were then used to calculate standardized seasonal 95th and 99th percentiles to measure storminess conditions (hereafter referred to as P95 and P99 respectively). Percentiles were calculated from the earliest possible date when all three stations in the triangle were reporting for the full season (e.g. the RDC geo-winds can be calculated from December 1884 onwards; see Table 1 and Fig. 1). Decadal scale variability of the resulting percentile timeseries was assessed using an 11-point Gaussian smoother (Wang et al. 2009), and linear trends were also calculated using a modified non-parametric Mann Kendall slope estimator (Wang and Swail 2001; Wang et al. 2009).

An additional aim of this study was to determine if there were any links between variations in storminess and the variability of rainfall in SE Australia. It is possible that storm activity and rainfall result from the same atmospheric processes so one might expect that there would be strong correlations between the two. In the last decade or so, SE Australia (SEA) has experienced a prolonged period of drought, with the largest rainfall decline occurring in autumn (Murphy and Timbal 2008). While this dry spell, averaged over the region as a whole, is of a similar severity to those which occurred at the beginning of the 20th century and in the late 1930s and 1940s, the recent dry has been exacerbated by much warmer temperatures in the present day compared with those previous events. For this reason we also look at links between each of the storm indices and the corresponding seasonal SEA rainfall (SEAR) anomalies obtained from BoM (here SEA is defined south of 33°S and east of 135°E, including Tasmania). The SEA rainfall data are derived from a gridded data set (Jones et al. 2009) with 0.05° resolution.

Results

In nearly all regions and seasons, linear trends estimated for both storm indices over the period analysed show a decrease (Table 2). In the majority of cases these trends are significant at the five per cent level. In autumn (MAM) and winter (JJA) significant declines are apparent in all regions in the P95 storm index, except for CDH (the most southerly triangle). In terms of the regional average series, all seasons show statistically significant declines in both storm indices, with the largest reductions in storminess in autumn and winter.

However, linear trends on their own represent little of the low-frequency variability that is present in these storm indices. Figure 2 shows the 11-point Gaussian low-pass filtered winter (JJA) P95 storm index series. In the late 19th century and early 20th century, decadal variability is large in all regions but this has reduced in later decades. The results are similar for all seasons and also for the P99 storm index (not shown). Of course the results are not independent between triangles because in a lot of cases they share a common vertex or vertices. However, even the timeseries and trends from the regions that do not share station locations are consistent.

Figure 3 shows the SE Australian regional average results for all seasons. The two storm indices are highly positively correlated (0.84, 0.77, 0.81 and 0.83 for DJF, MAM, JJA and SON respectively). For both storm indicators there is larger

[2]The only known exceptions are a small number of cases in which daylight saving time started later, or finished earlier, in South Australia than in New South Wales and/or Victoria, creating a 90-minute difference in the four western triangles. The most significant such period ran from 27 August to 29 October 2000.

Table 2. Linear trends (per decade) estimated for seasonal P95 and P99 storm indices over each of the triangle regions shown in Fig. 1 and for the average over southeast Australia (SEA). The start date of the trend estimate depends on when all three stations forming the triangle had data (see Table 1 and Fig. 2). Trends of at least five per cent significance are shown in bold.

Region	*P95 storm index*				*P99 storm index*			
	DJF	*MAM*	*JJA*	*SON*	*DJF*	*MAM*	*JJA*	*SON*
BGD	–0.0149	**–0.1521**	**–0.1040**	**–0.0524**	–0.0243	**–0.1127**	**–0.0767**	**–0.0466**
PBM	**–0.2090**	**–0.2080**	**–0.1642**	**–0.2161**	**–0.1397**	**–0.1568**	**–0.1424**	**–0.1623**
MBD	**–0.2350**	**–0.2193**	**–0.2232**	**–0.1960**	**–0.1693**	**–0.1755**	**–0.1533**	**–0.1632**
PMR	**–0.1660**	**–0.1385**	**–0.1292**	**–0.1130**	**–0.0898**	**–0.0771**	**–0.0584**	**–0.0668**
MDR	**–0.2250**	**–0.2070**	**–0.1910**	**–0.1946**	**–0.1643**	**–0.1820**	**–0.1395**	**–0.1763**
DGH	**–0.1442**	**–0.1248**	**–0.1130**	**–0.1285**	**–0.0974**	**–0.1010**	**–0.0707**	**–0.0792**
RDC	–0.0283	**–0.0582**	**–0.0576**	–0.0197	–0.0215	–0.0210	–0.0226	–0.0120
CDH	0.0193	0.0048	–0.0336	–0.0167	–0.0137	0.0176	–0.0310	–0.0087
SEA	**–0.1080**	**–0.1286**	**–0.1459**	**–0.1273**	**–0.0906**	**–0.1243**	**–0.1498**	**–0.1070**

Fig. 2 Low-frequency variability and linear trends of JJA P95 storm index series for each triangle. All trends shown are statistically significant at the five per cent level, except for CDH which is significant at the fifteen per cent level only (shown in cyan colour).

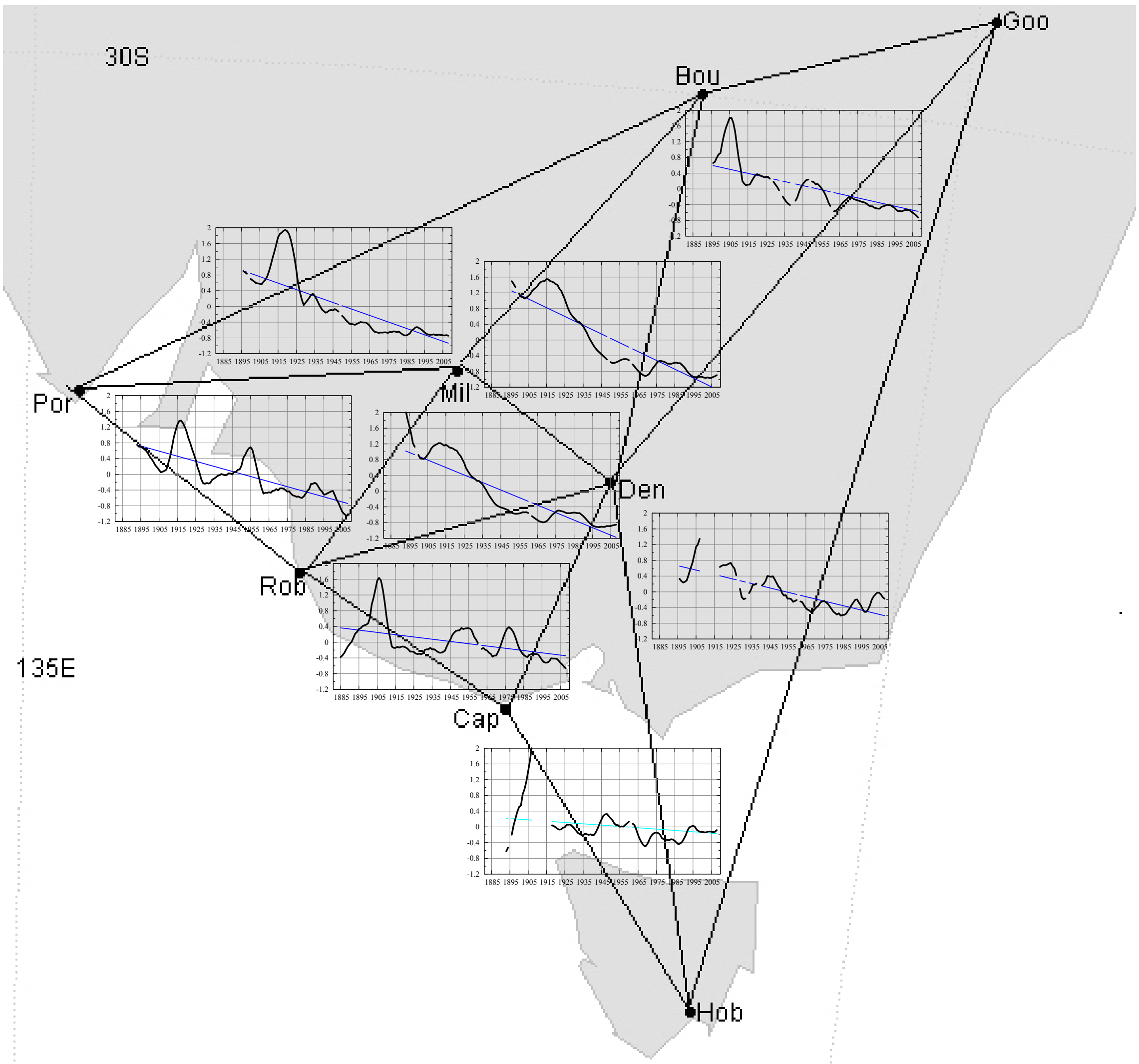
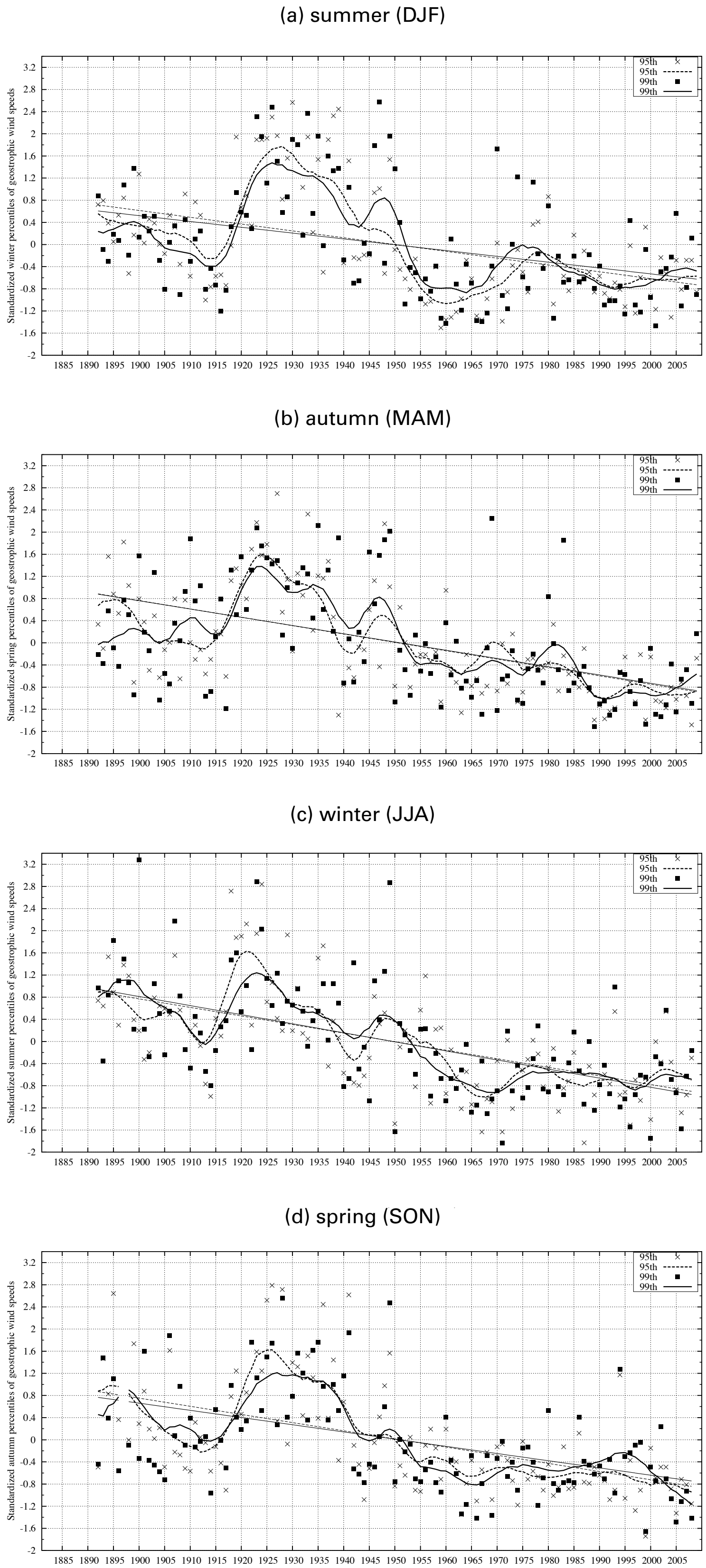


Fig. 3 Southeast Australian region averages of seasonal P95 and P99 storm indices, along with Gaussian filtered curves and linear trends for the indicated seasons over the period of 1885–2008.



decadal variability in the earlier part of the record. In all seasons there appears to be a peak in storminess around the 1920s with least activity around the 1960s. In the last couple of decades, storminess has 'rebounded' somewhat, except perhaps in spring (SON), but not nearly to the levels of the storminess peaks of the earlier part of the 20th century.

Table 3 shows the simultaneous correlations between seasonal SEAR anomalies and the regional P95 storm index series. Correlations for seasonal SEAR anomalies are based on data from 1900 onwards. Correlations for the P99 storm index are very similar although slightly smaller in general (not shown).

In summer (DJF) there is little correlation between storm activity and SEAR anomalies. This is not surprising because storm tracks shift greatly with season, and mid-latitude depressions and associated fronts are normally only minor contributors to summer rainfall in large parts of SE Australia, with incursions of tropical moisture, and convective activity, being more important. In autumn and winter there are generally small but statistically significant positive correlations with SEAR anomalies. In winter, six of the eight triangular regions have significant positive correlations with SEAR anomalies. Interestingly, in all seasons the storm index in PMR, one of the most westerly regions, is significantly correlated with SEAR anomalies but never explaining more than 28 per cent of variance. The largest absolute correlation (0.53) occurs in PMR in winter. Whilst a detailed analysis of synoptic/rainfall relationships has not been undertaken, it is worth noting that a common scenario for widespread autumn or winter rain over the SEA region (especially those parts north of the Great Dividing Range in Victoria, southern inland New South Wales, and to a lesser extent northern Tasmania) is a moist northerly flow ahead of an approaching low or front in the western part of the region (often centred in the PMR area), whereas very low pressure over Tasmania, typically associated with low values of the DGH and/or CDH index, is often associated with strong westerly or southwesterly flow over Tasmania and Victoria, normally bringing rain to relatively small areas in western Tasmania and southern Victoria but little or no rain over the larger areas north of the Great Dividing Range (Fig. 4).

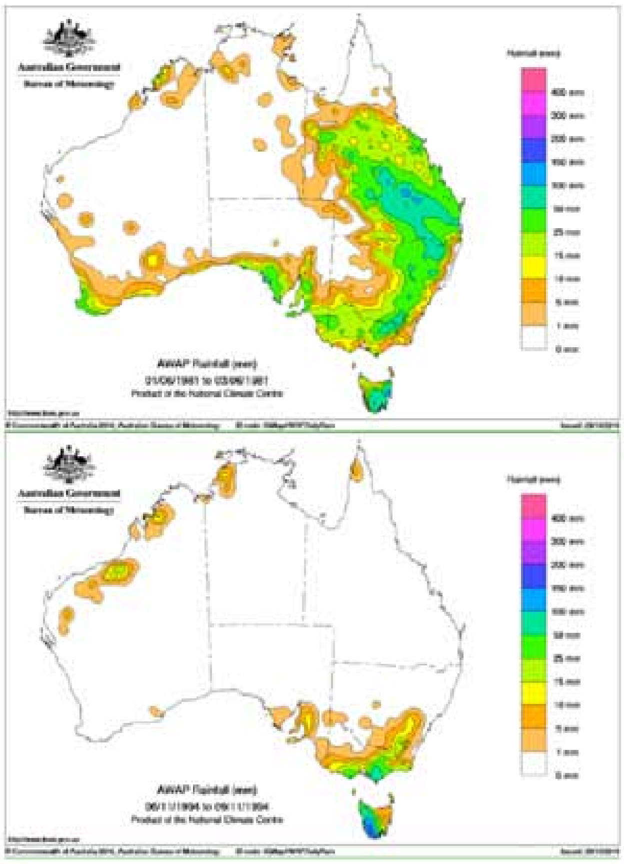
Table 3 Correlations between a seasonal southeast Australian rainfall (SEAR) anomalies and the seasonal P95 storm index for the indicated regions. Values of at least five per cent significance are shown in bold (both series were detrended for calculating correlations).

Region	*SEAR*			
	DJF	*MAM*	*JJA*	*SON*
BGD	–0.01	**0.28**	**0.21**	0.10
MBD	–0.12	0.13	**0.20**	0.14
PBM	–0.05	**0.20**	**0.38**	0.04
PMR	**0.20**	**0.29**	**0.53**	**0.36**
MDR	–0.11	0.15	**0.19**	0.19
RDC	–0.06	**0.21**	**0.34**	0.07
CDH	–0.09	–0.16	–0.00	**–0.28**
DGH	–0.03	–0.05	0.09	**–0.29**
SEA	–0.05	0.07	0.16	–0.12

The regional average storm index is not significantly correlated with the SEAR anomalies in any season over the century-plus record (see Table 3, last row). However, note that correlations in Table 3 refer to detrended timeseries, although both the magnitude and sign of correlations and significance are similar when trends are retained (not shown).

One could argue that it would be better to calculate correlations based on low frequency variations to better quantify the likely contribution of longer-term variations in storminess to longer-term variations of rainfall in SE Australia. However correlations calculated from decadally filtered values of the storms indices and SEAR anomalies were not dramatically different from those presented in Table 3. For example, the region-average decadally filtered correlations for P95 and SEAR anomalies were –0.01, 0.04, 0.22 and –0.25 (–0.16, 0.21, 0.31 and –0.34 without detrending) for DJF, MAM, JJA and SON respectively. This indicates that mechanisms in addition to changes in storminess are driving

Fig. 4 Event rainfall totals associated with the lowest recorded pressures at (top) Adelaide (in the PMR region) and (bottom) Low Head and Flinders Island (in the CDH and DGH regions). Rainfall totals are for the periods 1-3 June 1981 and 6-9 November 1994 respectively.



long-term changes in SE Australian rainfall. Other large-scale patterns have been linked to reductions in rainfall across southeast Australia including the Southern Annular Mode (SAM), El Niño – Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Verdon-Kidd and Kiem, 2009). The SAM is the dominant mode of Southern Hemisphere atmospheric circulation (e.g. Thompson and Solomon 2000) and it has been linked to changes and variations in Australian climate (e.g. Hendon et al. 2007; Meneghini et al. 2007; Watterson, 2009; Hill et al. 2009; Nicholls 2010) particularly during winter when a reduction in rainfall across parts of southern Australia is related to a poleward contraction of mid-latitude westerlies (i.e. the negative SAM phase). In addition, the IOD which represents fluctuations of warming and cooling in the Indian Ocean has been attributed to exacerbating drought conditions in SE Australia (Ummenhofer et al. 2009). However using measures of these large-scale indices and correlating them with the storms indices defined here, we found that individually there was no dominant process that was linked to the long- or short-term variations in storminess (not shown). Future work will include analysis of coupled climate simulations to help untangle the various contributing factors to this long-term decline in storminess and how it may or may not be linked to rainfall variability in the region.

Conclusions

Using geostrophic wind speeds derived from eight triangles of sub-daily MSLP observations, we calculated measures of storminess for SE Australia for the period from December 1884 to February 2009 for all seasons. Over the period analysed, storminess has reduced in almost all triangles and seasons, but particularly in autumn and winter. Reductions are statistically significant at the five per cent level in nearly all regions and seasons. In terms of the average over SE Australia, both storm indices show statistically significant declines in all seasons. There is strong decadal variability in storm activity particularly in the early part of the record, with storminess peaking in the 1920s. Decadal variability in storm activity has reduced in more recent decades in all seasons. There are statistically significant but small correlations between storminess in autumn and winter and SE Australian rainfall anomalies although this only applies to some regions, not to the regional average storm index.

The results show strong evidence for a significant reduction in intense wind events across SE Australia over the past century, consistent with a southward movement of southern hemisphere storm tracks. These changes can not explain the significant reductions that have been observed in rainfall in the region but in tandem with other climatic processes it remains likely that reductions in storminess are influencing observed drought conditions.

Acknowledgments

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