DOI: 10.22499/3.6901.014

JSHESS early online view

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Sensitivity of the orographic precipitation across the Australian Snowy Mountains to regional climate indices

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(Manuscript received April 2019; accepted July 2019)

The wintertime (May–October) precipitation across south-eastern Australia, and the Snowy Mountains, is studied for 22 years (1995–2016) to explore the sensitivity of the relationships between six established climate indices and the precipitation to the orography, both regionally and locally at high elevation areas. The high-elevation (above 1100 m) precipitation records are provided by an independent network of rain gauges maintained by Snowy Hydro Ltd. These observations are compared against the Australian Water Availability Project (AWAP) precipitation analysis, a commonly-used gridded nation-wide product. As the AWAP analysis does not incorporate any high-elevation sites, it is unable to capture local orographic precipitation processes. The analysis demonstrates that the alpine precipitation over the Snowy Mountains responds differently to the indices than the AWAP precipitation. In particular, the alpine precipitation is found to be most sensitive to the position of the sub-tropical ridge and less sensitive a number of other climate indices tested. This sensitivity is less evident in the AWAP representation of the high-elevation precipitation. Regionally, the analysis demonstrates that the precipitation to the east of the Snowy Mountains (the downwind precipitation) is weakly correlated with the upwind and peak precipitation. This is consistent with previous works that find that the precipitation in this downwind region commonly arises from mechanisms other than storm systems passing over the mountains.

1 Introduction

The Australian Alps are the highest part of the continental divide along the eastern seaboard, known as the Great Dividing Range, and play a crucial role in the weather across the densely populated southeastern seaboard. The Great Dividing Range forms the headwaters of many of the major rivers in the Murray–Darling basin and underpins many unique natural ecosystems of the high mountain catchments with some of the richest biodiversity areas on the mainland. The Alpine water accounts for 29% of the annual average inflow yield of the Murray-Darling Basin (Worboys and Good 2011). The Snowy Mountains, which reside along the Great Dividing Range, are the tallest mountains among the few alpine regions in Australia (Fig. 1, top panel). Precipitation over the Snowy Mountains has been of great interest among researchers, given its central role in feeding some of the major river systems of the Murray-Darling Basin, as well as providing hydroelectric power for much of eastern Australia.

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Two prolonged periods of dry conditions have been experienced in south-eastern Australia (south of 33.5 °S and east of 135.5 °E) in the past 100 years. An 11-year (1935–1945) and a 13-year (1997–2009) period both had rainfall deficits of above 10%, relative to the 1900–2009 long-term average. Much of southwest and southeast Australia underwent below-average to record-low rainfall during the peak of the Millennium Drought, which is defined by van Dijk et al. (2013) as the period 2001–2009: the longest consecutive series of years with below median rainfall in southeast Australia since at least 1900. The Millennium Drought had a significant impact on the Australian economy and led to large declines in agricultural employment and rural exports (Lu and Hedlry 2004). According to Bureau of Meteorology data (http://www.bom.gov.au/climate/drought/), in 2006, southeast Australia experienced its second-driest year on record since 1900, with below-normal annual precipitation. Nicholls (2005) reported a decreasing trend in both maximum, from about 210 cm to about 190 cm, and spring snow depth, from around 175 cm to about 100 cm, in the Snowy Mountains over a 40-year period beginning in 1962. A decline of about 10% was observed in the maximum snow depth over this period. A much larger decrease in spring snow depth (about 40%) was also observed, mostly attributed to the melting of the snow due to a combination of a slight decline in winter precipitation and a strong warming trend during July–September.

Risbey et al. (2009) suggested that precipitation across Australia, and in particular southeast Australia, is generally governed by large-scale climate drivers such as the El Niño-Southern Oscillation (ENSO) Index, Southern Annular Mode (SAM), Indian Ocean Dipole (IOD) and the Atmospheric Blocking Index (ABI) at the longitude of 140˚E. They found the ABI to be the dominant climate driver for winter precipitation across southeast Australia. Timbal and Drosdowsky (2013) linked the spatial and temporal rainfall decline in southeast Australia to the position (STR-P) and intensity (STR-I) of the subtropical ridge during 1997–2009. Grose et al. (2015) found this same relationship in historical Coupled Model Intercomparison Project phase 5 (CMIP5) simulations. Several studies have documented the sensitivity of precipitation in southeast Australia to the Southern Oscillation Index (SOI; as an indicator of ENSO), indicating higher mean monthly precipitation during La Niña events (e.g., Gallant et al. 2012, Murphy and Timbal 2008, Ummenhofer et al. 2011, Cai et al. 2011, Pepler et al. 2014, Theobald and McGowan 2016).

For many of these studies, the precipitation over southeast Australia has commonly been defined from a precipitation analysis product, such as the Australian Water Availability Project (AWAP; Jones et al. 2009), for a specified domain. The correlation of the average precipitation over the domain with the specific climate index establishes the strength of any relationship. As there is no single fixed definition of southeast Australia, these studies have commonly defined a broad domain that can average over orographic and non-orographic regions, even though the Snowy Mountains have been found to greatly affect the precipitation both regionally (e.g. Timbal 2010, Pepler et al. 2014) and locally over the peaks (Chubb et al. 2011, Huang et al. 2018). On a regional scale, mountains can block an advancing airmass and its precipitation, diverting it rather than having it pass over the top. Locally, orographic precipitation can arise from a variety of dynamical and microphysical processes that are not present at upwind and downwind sites. For instance, Houze (2012) identified twelve distinct orographic processes that can create, enhance and/or redistribute precipitation.

Detailed case studies of wintertime precipitation events over the Great Dividing Range have found that post-frontal orographic rainfall can make a substantial contribution to total precipitation (Chubb et al. 2012, Sarmadi et al. 2019). Chubb et al. (2011) details that the Southern Ocean serves as the source of water for this post-frontal air mass, being converted to precipitation when lifted over the Snowy Mountains. Overall, they found that the wintertime precipitation over the Snowy Mountains was approximately a factor of four greater than for an upwind site over the Mallee. Chubb et al. (2016) employed a high-density network of rain gauges over the Snowy Mountains to evaluate the AWAP precipitation product finding that the analysis underestimated precipitation on the upwind slopes of the mountains, while slightly overestimating the downwind precipitation. While the AWAP product makes corrections for altitude, it does not account for upwind/downwind effects. Lewis et al. (2018) studied these biases over western Tasmania demonstrating that the AWAP precipitation analysis may not fully capture the common effect of orographic blocking. Huang et al. (2018) evaluated the Bureau of Meteorology operational forecasts of precipitation with the same network of high elevation rain gauges over the Snowy Mountains, finding that the unique microphysics over the Snowy Mountains (Morrison et al. 2013) may be important in the generation of precipitation in the Alpine regions. Sarmadi et al. (2019) studied the sensitivity of numerical simulations of precipitation over the Snowy Mountains to the microphysics scheme, highlighting how the conversion of commonly-observed supercooled liquid water to ice affected the distribution of precipitation across the mountains.

The complexity of wintertime orographic precipitation over the Snowy Mountains suggests that it may not be well-represented by a precipitation analysis that does not directly incorporate high elevation surface observations, such as AWAP (Chubb et al. 2016). Accordingly, the correlation between the average regional precipitation and a given climate index may not apply to the high-elevation orographic precipitation. Similarly, a single correlation over a broad region may not reveal variations arising from the orography. Given the importance of the precipitation across southeast Australia, and the Snowy Mountains in particular, the aim of this study is to explore the sensitivity of the relationships between climate indices and the precipitation to the orography, both regionally and locally at high elevation areas. Unlike the previous climate studies mentioned, independent high-elevation rain gauge observations are employed in this analysis.

2 Precipitation data sources

The analysis is limited to the 22-year period (1995–2016), wintertime only (May-October) being constrained by the availability of high-quality, high elevation, surface observations from Snowy Hydro Ltd. (SHL).

2.1 SHL ground-based wintertime (May-October) precipitation dataset

Local, high-elevation precipitation across the Snowy Mountains is obtained from seven well-maintained weather stations above 1100m, operated by SHL. Half-hourly precipitation amounts are accumulated from 0900 local time (2300 UTC) to the same time of the next day, and then these daily precipitation values are aggregated to yield monthly totals. For the 22-year winter period (May–October) considered in this study, about 80% of all days have at least five stations that had suitable quality flag contributing to the mean value; data flagged as unsuitable are removed. No systematic bias in missing or flagged data has previously been noted. The locations, elevations, operating year of the gauges and their fairly uniform long-term mean wintertime precipitation are shown in Table 1; Figure 1 shows a map of their locations. A more complete description of the instrumentation and this data set can be found in Chubb et al. (2016). These seven high-elevation surface records have commonly been averaged together to represent the precipitation across the Snowy Mountains (e.g. Sarmadi et al. 2019) and is hereafter referred to as SHL 7-site average. The precipitation from these sites is not employed in the production of the AWAP analysis, making it an independent data set that can be employed for evaluation purposes (Chubb et al. 2016).

Table 1 Properties of seven SHL precipitation gauges. A basic summary of the total wintertime precipitation and quartiles (Q1, Q2, Q3) is calculated over the period 1995–2016.

Site	*Start Date*	*Elev (m)*	*Lat (˚S)*	*Lon (˚E)*	*Mean (mm)*	*Q1 (mm)*	*Q2 (mm)*	*Q3 (mm)*
Cabramurra	1955	1473.23	-35.94	148.39	858.3	710.3	849.5	931.9
Guthega PS	1994	1320.76	-36.35	148.41	975.9	841.8	996.7	1108.5
Guthega Dam	1992	1586.11	-36.38	148.37	899.3	735.4	903.1	1032.8
Jagungal	1990	1682.37	-36.14	148.39	1134.7	923.7	1094.3	1287.8
The Kerries	1995	1741.32	-36.26	148.38	1031.9	880.3	1095.6	1195.8
Tooma Dam	1992	1221.93	-36.05	148.28	1176.9	1007.9	1175.3	1313.6
Geehi Dam	1992	1160.56	-36.30	148.31	1078.8	939.6	1097.3	1248.6

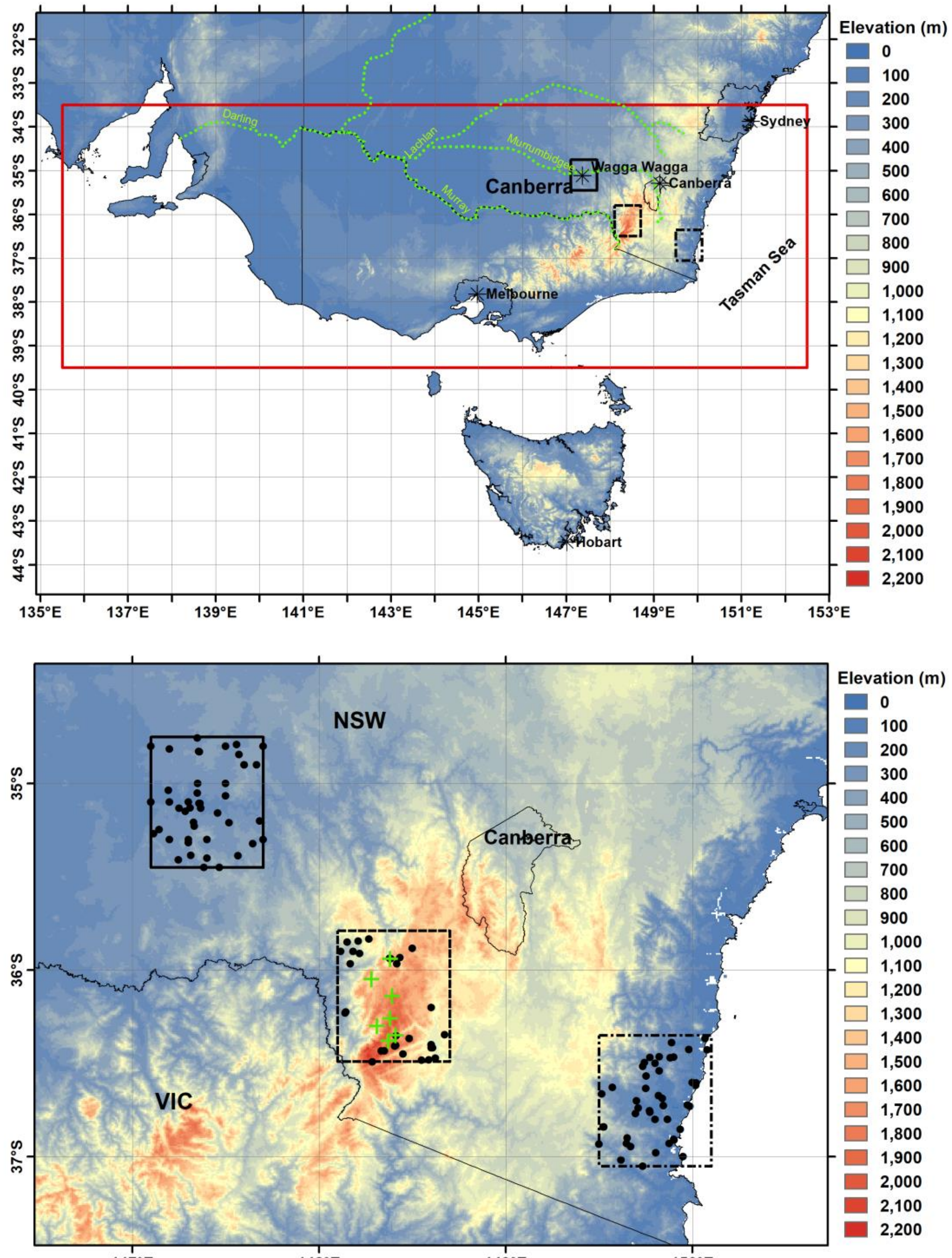

Figure 1. (Top plot) Topographic map of southeastern Australia showing major rivers (green dots), main cities and the closest upper-wind site of the BOM to the Snowy Mountains (Wagga Wagga), with the area defined as SEA-domain (red box). (Bottom plot) Zoomed-in view of the three other precipitation domains used in this study (West-domain in solid line, Peak-domain in dashed line and East-domain in dashed-dotted line). Other features include the location of the seven SHL and BOM rain gauges in blue plus signs and black dots, respectively.

2.2 The Australian Water Availability Project (AWAP)

The Australian Water Availability Project (AWAP; Jones et al. 2009) provides a national gridded product with the aim of monitoring the terrestrial water balance across the entire Australian continent. The AWAP analysis interpolates the Australian Bureau of Meteorology (BOM) rainfall gauge data with splines at a spatial resolution of 0.05° × 0.05° from 1900 to the present. The average precipitation of the seven AWAP grid cells closest to the seven Snowy Hydro high-elevation rain gauges (AWAP 7-site average) is used to study the sensitivity to local orographic processes. Following Chubb et al. (2011) a high-elevation domain (Peak-domain) is defined (35.4°–36.8° S and 147.8°–149° E) over the Snowy Mountains, which will also be used to study the sensitivity to local orographic processes.

The Peak-domain is also used to study the sensitivity of the regional precipitation to orographic processes along with an upwind domain (West-domain: 34.4°–35.8° S and 146.8°–148° E) and a downwind domain (East-domain: 36.0°–37.4° S and 149.2°–150.4° E). The West-domain and East-domain are close to the Snowy Mountains, but are at low elevations. Finally, a broad, regional domain covering SE Australia (33.5°–39.5° S and 135.5°–152.5° E) is defined (SEA-domain), which incorporates both orographic and non-orographic terrains. The domains defined in this study are shown in Figure 1.

2.3 High Elevation Precipitation

Figure 2 shows the wintertime precipitation over the 22-year period for all four domains and two site averages (SHL 7-site average and AWAP 7-site average). Wintertime precipitation over the high elevations of the Snowy Mountains (SHL 7-site average) is highly variable with extremes of 430 mm in 2006 and 1540 mm in 2016 occurring within the 22-year period.

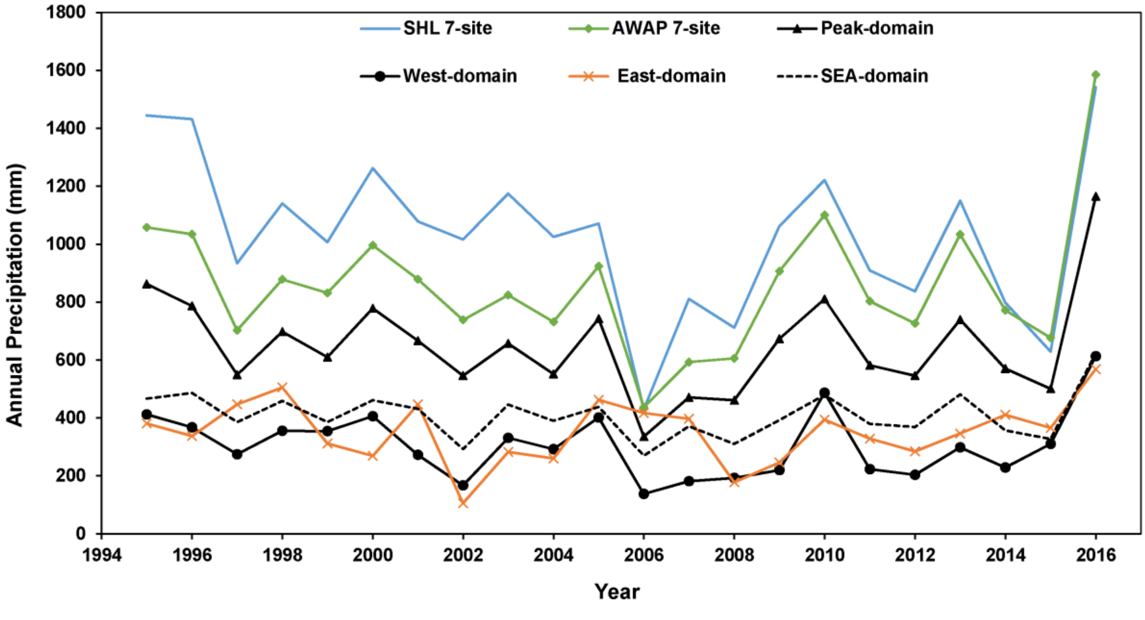

Figure 2 May–Oct total monthly precipitation for the period 1995–2015 across different precipitation areas.

Three high elevation precipitation areas (SHL 7-site average, AWAP 7-site average and Peak-domain) have the greatest precipitation for each of the 22 years, as expected, again demonstrating the importance of the orographic enhancement. Given that the Peak-domain is averaged over the entire box, it includes terrain below 1100 m elevation. Accordingly, it has less precipitation than the other two high-elevation averages. The correlation between the AWAP 7-site and the Peak-domain is 0.99, however; both AWAP 7-site average and Peak-domain are essentially using the same lower-elevation sites. Differences between these two domains largely reflects the altitude scaling within the AWAP algorithm (Chubb et al. 2016), suggesting that they will display similar relationships to any climate indices. Ideally, the SHL 7-site average and AWAP 7-site average should be quite similar. In practice, however, the SHL 7-site average precipitation is greater for 20 of the 22 years, further illustrating the shortcomings of the AWAP analysis to capture local orographic enhancement when it is not directly observed (Chubb et al. 2016). Despite this shortcoming, the SHL 7-site average is strongly correlated (0.85) with both the AWAP 7-site average and the Peak-domain.

The monthly progression of the SHL 7-site and AWAP 7-site average precipitation may be further explored to better illustrate their differences (Table 2). The wintertime precipitation follows a seasonal cycle similar to that in Chubb et al. (2011) with the peak precipitation in August (199.55 mm for SHL 7-site and 150.32 mm for AWAP 7-site). For the six-month average, the AWAP 7-site (142.76 mm) is approximately 17% less than SHL 7-site (171.95 mm). The overall RMSE is 50.6 mm with a bias of -29.2 mm. The RMSE and bias values similarly follow a seasonal cycle, peaking in midwinter. We note that are the SHL observations not incorporated into the AWAP analysis (Chubb et al. 2016). Further, the Bureau of Meteorology rain gauges used in AWAP are unable to record frozen precipitation rates greater than about 3 mm/hr (Gorman 2003). Lower interquartile range (IQR; 25th to 75th percentile) and standard deviation values in the AWAP 7-site average (IQR=79 mm, SD=63 mm) in comparison with the SHL 7-site average (IQR=115, SD=78 mm) reflects weaker variability in the AWAP product. It is expected that site measurements (SHL 7-site average) will display greater variability than gridded analysis products (AWAP 7-site average) in complex terrain (Chubb et al. 2016).

Figure 3 shows the marginal distributions of the monthly precipitation from SHL 7-site average and AWAP 7-site average, which are displayed on the horizontal and vertical axis of a scatter plot, respectively. The identity line is added for reference, showing an underestimation by AWAP of up to 77% for wintertime monthly precipitation over seven gauges. This underestimation by AWAP occurs 75% of the time, leading to an underestimation of 24% on average.

Table 2 Performance of AWAP precipitation at high-elevation gauges over the period of 1995–2016. Here the monthly values of the AWAP_7sites are compared with SHL_7sites in mm.

	SHL Mean (mm)	*AWAP Mean (mm)*	*RMSE*	*Monthly Bias*	*Correlation*
May	128.68	109.76	27.55	16.39	0.95
June	185.63	151.94	59.67	-33.69	0.81
July	181.82	148.56	54.75	-33.26	0.68
August	199.55	150.32	64.40	-49.23	0.82
September	191.33	159.84	53.59	-31.49	0.84
October	144.67	136.17	32.13	-8.51	0.92
Wintertime	171.95	142.76	50.63	-29.18	0.85

2.4 Regional Precipitation

Looking at the regional effect of orography on precipitation, the East-domain, West-domain and SEA-domain all have less wintertime precipitation than the high elevation areas, as expected (Fig. 2). Over the 22-year period, the mean annual rainfall of SHL 7-site average is ~3 times greater than the West-domain. Table 3 shows that the West-domain correlates relatively strongly with the Peak-domain (0.75) and the SHL 7-site average (0.62), as anticipated. The weaker correlation with the SHL 7-site average further illustrates that any local orographic enhancement to precipitation may not be captured in the AWAP analysis.

On average, the East-domain is wetter than the West-domain, which may be counterintuitive. While downstream precipitation is commonly expected to be drier than an upwind site, as water is removed in transit, the opposite can also occur depending on the exact mechanisms that are driving the precipitation (Houze 2012). This suggests that the wintertime precipitation in the East-domain is likely to be arising from different events/systems than over the West-domain. The East-domain is poorly correlated with all of the others, particularly the SHL 7-site average at only 0.01 correlation, which further suggests that the wintertime precipitation events within this domain are not related to those in the upwind and high elevation domains. These findings are in alignment with Timbal (2010), who showed that the eastern seaboard area (coastal strip on the eastern side of the Great Dividing Range, covering the East-domain in this study), does not appear to have the same strong relationship with the key climate indices as in other regions of southeast Australia. For instance, the intensity of the subtropical ridge does not significantly impact the rainfall in this area (dissimilar to other parts of south east Australia), while a southwards shift of the subtropical ridge likely causes rainfall to increase in the region.

The broader, regional SEA-domain is more strongly correlated with the West-domain (0.74) and Peak-domain (0.74) than the East-domain (0.44), which is expected; the SEA-domain largely covers terrain to the west of the Great Dividing Range.

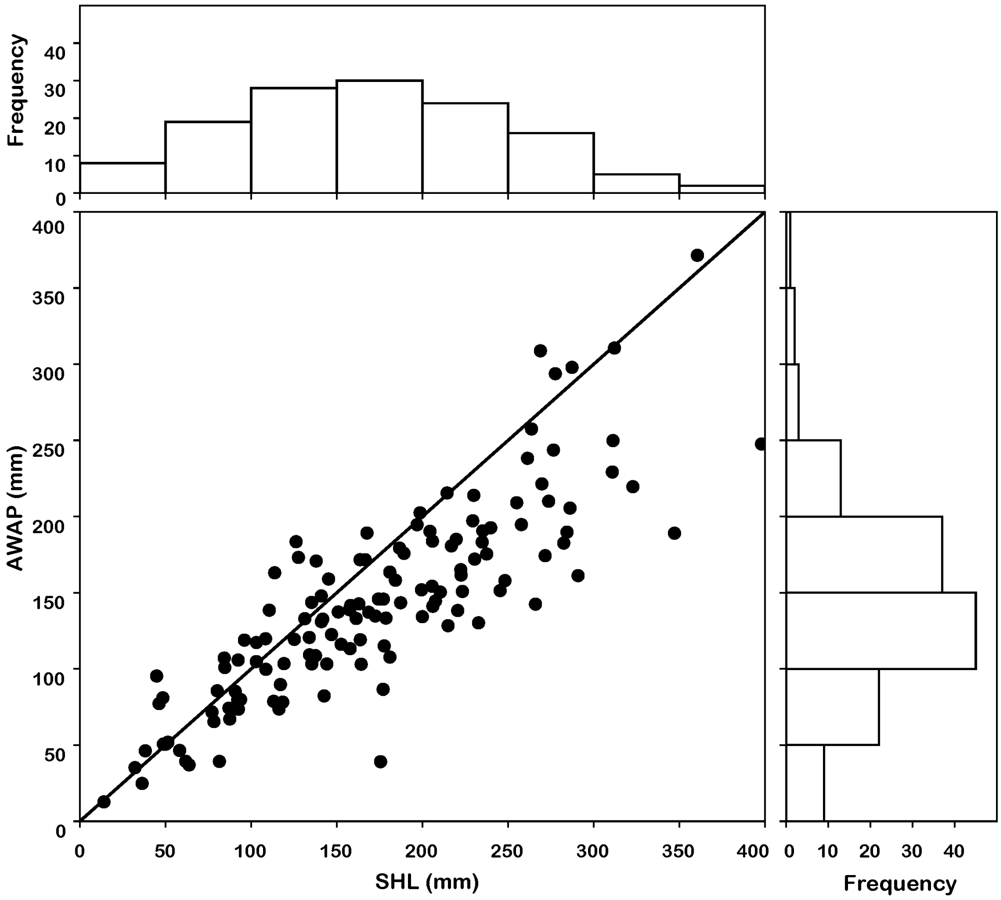

Figure 3 Histogram and scatterplot of AWAP 7-site average and SHL 7-site average May–Oct total monthly precipitation (in mm) for the period 1995–2016.

3 Climate Indices

In this study we consider the four climate indices discussed in Risbey et al. (2009), namely the SOI, the SAM, the ABI and the IOD. Further we consider the intensity (STR-I) and location (STR-P) of the subtropical ridge, as defined in Timbal and Drosdowsky (2013). Given that an aim of this research is to explore the sensitivity of orographic precipitation to well-known climate indices, it is worthwhile to first examine the cross-correlation coefficients between these six large-scale indices (Table 3. bottom six rows). Statistically significant correlations at p = 0.05 are in bold. Observed interactions between climate indices may confound the interpretation of correlations between the climate indices and the precipitation.

The cross-correlation coefficients for the six winter months over the 22-year period suggest a large degree of independence between all indices with the greatest correlation (-0.38) found between the IOD and SOI. The IOD (also known as the Dipole Mode Index or DMI) is a measure of the anomalous zonal sea surface temperature gradient across the equatorial Indian Ocean and has commonly been linked with the SOI, a measure of pressure difference anomaly between Tahiti and Darwin (e.g., Ashok et al. 2003).

Table 3 The Pearson correlation coefficients of monthly winter precipitation and large-scale indices of rainfall over the period 1995-2016. Statistically significant (at the 0.05 confidence level) values are in bold. The seasonal cycle is not removed. The shaded region records the correlations between monthly wintertime precipitation and the six climate indices.

Pearson Correlation	*SHL 7-site*	*AWAP 7-site*	*Peak-domain*	*West-domain*	*East-domain*	*SEA-domain*	*STR-I*	*STR-P*	*SOI*	*SAM*	*ABI*	*DMI*
SHL 7-site	1	**0.85**	**0.85**	**0.62**	0.01	**0.64**	**-0.27**	**-0.60**	**0.26**	-0.15	**0.18**	**-0.37**
AWAP 7-site		1	**0.99**	**0.73**	**0.28**	**0.72**	**-0.32**	**-0.44**	**0.32**	0.08	**0.20**	**-0.39**
Peak-domain			1	**0.75**	**0.32**	**0.74**	**-0.30**	**-0.42**	**0.30**	0.08	**0.23**	**-0.38**
West-domain				1	**0.20**	**0.74**	-0.13	**-0.26**	**0.33**	**0.22**	**0.38**	**-0.32**
East-domain					1	**0.44**	-0.07	**0.26**	0.02	**0.23**	**0.23**	-0.13
SEA-domain						1	-0.10	**-0.24**	**0.29**	0.11	**0.59**	**-0.41**
STR-I							1	**0.36**	**-0.25**	**0.31**	0.10	0.09
STR-P								1	-0.13	**0.33**	0.01	0.11
SOI									1	0.02	0.10	**-0.38**
SAM										1	0.16	-0.07
ABI											1	-0.05
DMI												1

The positive cross-correlation between the STR-I and STR-P (0.36) is not unexpected either; Timbal and Drosdowsky (2013) found significant correlation between the two STR series from April to December (1890–2009). Cai et al. (2011) found that a positive IOD tended to increase both the STR-I and STR-P, which is also found over this limited time period (cross correlations of 0.09 and 0.11, respectively), but not statistically significant.

The Atmospheric Blocking Index (ABI) is another regional synoptic feature of the winter circulation. It depends on the zonal components of the mean 500-hPa wind at several latitudes. The mathematical expression of this index is

$$ABI = 0.5 \times (U_{25} + U_{30} + U_{55} + U_{60} - U_{40} - U_{50} - 2U_{45}) \quad (1)$$

where UL represents the zonal component of the mean 500-hPa wind at latitude L (Pook and Gibson 1999). Following Risbey et al. (2009), wind data from the National Centers Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR reanalysis dataset) are utilized at 140˚E (a typical longitude for Atmospheric Blocking in the Australian region) to compute the ABI index. Over the 22-year period the ABI is not found to be significantly correlated with any of the other climate indices.

The last relationships of significance between climate indices is between the SAM and the STR-I (0.31) and STR-P (0.33), which is also understandable. The SAM reflects the poleward contraction of the westerly belt that encircles Antarctica and is found to be a dominant mode of atmospheric variability in the mid/high latitudes in the Southern Hemisphere (Thompson and Solomon 2002). Marshall (2003) calculated this index using the mean Mean Sea Level Pressure observations from six stations as a proxy of the zonal mean at both 40˚ and 65 ˚S from 1958 to present, and their calculated output is used here. The latitude of the westerly belt over the Southern Ocean is not independent of the latitude or strength of the subtropical ridge (CSIRO and Bureau of Meteorology 2015).

4 Impact of climate indices on precipitation

4.1 High-elevation precipitation

The shaded region of Table 3 records the correlations between monthly wintertime precipitation (SHL 7-site average, AWAP 7-site average and the four domains) and the six climate indices. Focussing on the three high-elevation domains, the AWAP 7-site average and Peak-domain behave similarly against all six climate indices, as expected. The peak correlation is between the STR-P and AWAP 7-site average (-0.44), which is understandable. More southerly subtropical ridge may suppress convection that is needed for heavier precipitation. This suppression is even stronger for the SHL 7-site average (-0.60); local orographic enhancement at the high elevations over the Snowy Mountains may be particularly sensitive to suppression from the subtropical ridge. The strength of the subtropical ridge (STR-I) is also significantly correlated with these high elevation sites at -0.27, -0.32 and -0.30 for the SHL 7-site average, AWAP 7-site average and Peak-domain, respectively.

The May–Oct cycle of the STR-P and STR-I averaged across the periods of this study (1995–2016) has been plotted and compared with the long-term (1890–2015) climatology of Timbal and Drosdowsky (2013). The trend of monthly mean subtropical ridge over the 22-year period displays a noticeable anomaly towards greater intensity and more southerly location (not shown). A similar finding was also reported by Timbal and Drosdowsky (2013) across a period of low rainfall (1997 to 2009) associated with the Millennium Drought, with a noticeable anomaly in autumn to early winter. This shift in the location of the STR-P has been attributed to the poleward expansion of the descending arm of the southern hemisphere Hadley cell (e.g. Seidel et al. 2007, Nguyen et al. 2013).

Beyond the STR-P, the next strongest climate driver of significance is the IOD at -0.37, -0.39 and -0.38 for the SHL 7-site average, AWAP 7-site average and Peak-domain, respectively. The IOD, the sea surface temperature anomaly difference between the tropical western and southeastern Indian Ocean, has commonly been found to modulate rainfall across southeastern Australia (e.g. Ashok et al. 2003, Ummenhofer et al. 2011, Pepler et al. 2014).

Measuring the anomaly of pressure difference between Tahiti and Darwin is related to the location of deep convection over the tropical Pacific Ocean and the Walker circulation. The ensuing circulation has been found to change weather patterns across the globe through a variety of proposed teleconnections. The SOI is a strong climate driver of precipitation across much of Queensland (e.g., Risbey et al. 2009). The SOI has a significant positive correlation with rainfall over southern Australia during the late winter and early spring (Risbey et al. 2009). Negative SOI values (El Niño conditions) generally decrease the mean rainfall in southern Australia in the winter and spring months (Murphy and Timbal 2008, Nicholls 2010). The correlation between the SOI and high elevation precipitation is significant at 0.26, 0.32 and 0.30 for the SHL 7-site average, AWAP 7-site average and Peak-domain, respectively.

Atmospheric Blocking at 140oE is often linked to extended dry periods in southern Australia during winters (Pook et al. 2006). For our 22-year period examined in this study, relatively weak, but significant correlations were found between the precipitation over the high elevation and the ABI.

The SAM has previously been linked to winter rainfall over southern Australia (e.g. Meneghini et al. 2007). Chubb et al. (2011) reported about 30% less wintertime (May–Sep, 1990–2009) precipitation during the positive phase of SAM in the high-elevation gauges over the Snowy Mountains (SHL 7-site average). The positive phase of SAM shifts the belt of strong westerly winds poleward, whereby diminishing westerly winds over the southeast Australia during winter (Hendon, Thompson, and Wheeler 2007). Conversely, a negative SAM brings more fronts and moisture to the southern portion of Australia. This relationship, however, is not seen to extend to the high elevation domains at a level of statistical significance for the period of this analysis.

4.2 Regional precipitation

Finally, we turn our attention to the correlation between the climate indices and the regional precipitation domains (West-domain, East-domain and SEA-domain) Once again, the East-domain behaves quite differently from the other domains (including the high elevation areas) for many of the climate indices largely consistent with Timbal et al. (2010). The East-domain is positively correlated with the STR-P and is not significantly correlated against either the SOI or the IOD.

The West-domain and SEA-domain largely have similar behaviour to one another, except against the SAM index. The West-domain and SEA-domain do behave differently from the high-elevation precipitation areas for STR-I (no significance), STR-P (weaker correlation), SAM (stronger correlation) and ABI (stronger correlation). It is worth highlighting the strong positive correlation between SEA-domain and the ABI at 0.59, which is much higher than the correlation of the ABI with any of the other three domains and two 7-site averages. This strong relationship is consistent with Risbey et al. (2009).

5 Conclusions

The primary aim of this research has been to examine the relationship between six established climate indices on precipitation across southeast Australia with a particular focus on the orographic precipitation over the Snowy Mountains. The analysis explores not only the precipitation generated at the high elevation alpine sites, as observed by the SHL rain gauges, but the changes in the regional precipitation when moving across the Snowy Mountains. Three high elevation precipitation areas (SHL 7-site average, AWAP 7-site average and Peak-domain) are considered, as well as an upwind area (West-domain), and downwind area (East-domain) and a single, broad regional domain that covers all of SE Australia (SEA-domain), including all orographic regions. The SHL 7-site average is produced from independent surface observations made by Snowy Hydro Ltd. These data are available for a 22-year period (1995–2016), wet season months only (May–October). Precipitation for the AWAP 7-site average and other four domains is taken from the AWAP product. While a 22-year period is admittedly short for undertaking climate analysis, the behaviour of the precipitation and the climate indices over this 22-year period is largely consistent with studies covering longer periods of time, where orographic precipitation was not explicitly considered.

Looking first at the regional effect of the Great Dividing Range on the impact of the various climate indices, the downwind precipitation (East-domain) is not correlated with the upwind (West-domain) or high elevation (Peak-domain) precipitation. This suggests that the precipitation over the East-domain arises from different weather systems from those that commonly are observed to move from the west across southeast Australia during the wet season (Bertrand Timbal 2010). Correspondingly, the climate indices typically have vastly different relationships with this precipitation than with the upwind and high elevation domains. For example, there is a positive correlation with the STR-P for this domain. The STR-P is negatively correlated with the others. In addition, the East-domain is not significantly correlated with either the SOI or the IOD; this contrasts with the observed strong significant relationships between these two indices and the other areas. This is likely due to the fact that the IOD tends to influence Australian rainfall via the SST anomalies, setting up in the region northwest of Australia (Risbey et al. 2009).

It may also be concluded that there is limited value in including this portion of southeast Australia in a large regional domain (SEA-domain) as is commonly done. Mixing regions of different behaviours greatly complicates a deeper understanding of observed relationships.

Looking at the difference in correlations between the upwind (West-domain) and broad (SEA-domain) and the high elevation areas (SHL 7-site, AWAP 7-site and Peak-domain), some immediate differences are evident. The high-elevation sites are more sensitive to the STR-P, STR-I and SAM but less sensitive to the SOI and ABI.

Focussing exclusively on the high elevation areas, the SHL 7-site average incorporates only the high-elevation (above 1100 m) surface sites from Snowy Hydro. The two AWAP based precipitation products (AWAP 7-site average and Peak-domain) do not have access to these observations, ingesting observations from lower elevations into the product. These two AWAP based precipitation products behave similarly across all aspects of this study. Most notably, the SHL 7-site average is most strongly correlated with the STR-P (0.60) and more weakly correlated with the STR-I, SOI and ABI than the two AWAP high elevation areas. The influence of the ABI on the SHL 7-site average is the weakest amongst the different areas examined in this study. This, presumably, reflects the role of rainfall from orographic uplift in westerly streams that are not common in blocking situations. One of the major insights gained from this analysis is that the wintertime precipitation over the Snowy Mountains is most sensitive to the position of the sub-tropical ridge. At face value, this relationship is reasonable: as the ridge moves further south it suppresses convection over the Snowy Mountains. A more detailed understanding of the changes in the dynamical, and possibly microphysical, processes that lead to suppressed precipitation may be a focus of future studies.

Acknowledgments

This study is supported by Australian Research Council Linkage Project LP160101494. We are grateful to Snowy Hydro Ltd. for providing the precipitation data for the Snowy Mountains.

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