South Eastern Australian
Climate initiative

Project 1.1.1

Documenting changes in south-eastern Australian rainfall, temperature, surface humidity and pan evaporation

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Initial Project objectives:

- To extract relevant datasets and generate climatologies to validate model outputs in the rest of the program (in particular Themes 2 and 3);
- To produce a report on observed trends and decadal changes in south-eastern Australian climate; and
- To identify gaps and uncertainties in current knowledge and observational datasets.

Proposed methodology

This project will investigate the utility of the Bureau of Meteorology's (BoM) high quality datasets for characterising recent climate variability in south-eastern Australia (SEA). Variables to be examined are rainfall, maximum and minimum temperature, surface humidity, and pan evaporation at daily to decadal time scales. This is the first time that such a comprehensive analysis has been undertaken in Australia.

It also aims to investigate the possibility of using additional stations to complement the patial and temporal coverage of the high quality network and, when possible, identify gaps in the spatial coverage of the observation networks for the variables listed above and their records. Then, using the datasets outlined above, this project will assess the extent to which recent climatic trends depart from those of the past. It will then document the behaviour of the primary modes of climate variability affecting south-eastern Australia, such as the El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM), over the historical record and determine their relative and joint contributions to observed long-term trends.

Summary of the findings:

- Datasets are now available for SEACI-wide station data of daily values of rainfall, temperature, humidity and pan evaporation. The dataset combines stations of the highest possible quality with additional stations when necessary to enhance spatial coverage.
- Based on this dataset, most of SEA south of 33 °S has had rainfall for 1997–2006 in the lowest 10 per cent on record. Only one previous 10-year period had average rainfall over SEA less than the current average (1935–1945).
- Most of the rainfall decline in SEA has come in the autumn season (72 per cent). In addition, year-to-year variations in annual mean rainfalls over SEA have been the lowest on record. Furthermore, the recent dry period has been compounded by an underlying warming trend.

- The main driver of SEA rainfall is the surface air pressure. Mean sea level pressure (MSLP) has been trending toward higher values and the relationship with lower rainfall is strong in most seasons and explains the rainfall decline.

- No single large-scale mode of variability appears sufficient to explain the rainfall decline, but several have an impact on the regional climate. The combination of the most relevant factors differs from one part of the SEACI study area to another.

Assembling climatological dataset specific for SEACI

A database of surface meteorological variables relevant to the SEACI program has been assembled. Variables are daily values for rainfall, daily extreme temperature (Tmax and Tmin), dew point temperature (daily extreme: dTmax, dTmin and 10 am local time value: dT10), relative humidity (derived from dT10) and pan evaporation.

The spatial extension of the data retained was decided using climate entities encompassing the agreed SEACI domain (Drosdowsky, 1993). For each variable the cornerstone was the High Quality (HQ) network developed over the last 10 years by BoM, described in detail in the relevant literature, and of the highest quality by international standards. Beside the HQ network, additional data from BoM archive was sought in order to, when possible, enhanced the spatial coverage. The focus was on stations with daily data extending back to 1958 still open today, and with few missing data. This date (1958) corresponds to the start of the re-analyses period where more detailed scientific investigations are possible. This search was done for rainfall and temperature only as dew point HQ is already limited by this criteria (all stations go back no further than 1957) as is pan evaporation HQ (data go back to 1975 only).

A total of 585 rainfall stations have been chosen (Fig. 1). 95 stations are from the HQ rainfall network (Lavery et al., 1992 and 1997), updated in 2006, with some observations dating back to the late 19th century. Additional stations with less than five per cent of missing data (and less than three per cent since 1996) were chosen to provide a higher density network. In addition, data approaching these standards were extracted to fill spatial gaps in the coverage. Amongst these stations some have been flagged as potentially problematic due to poor observing practices. Some additional information on the data quality at selected rainfall stations is provided in Appendix 1.

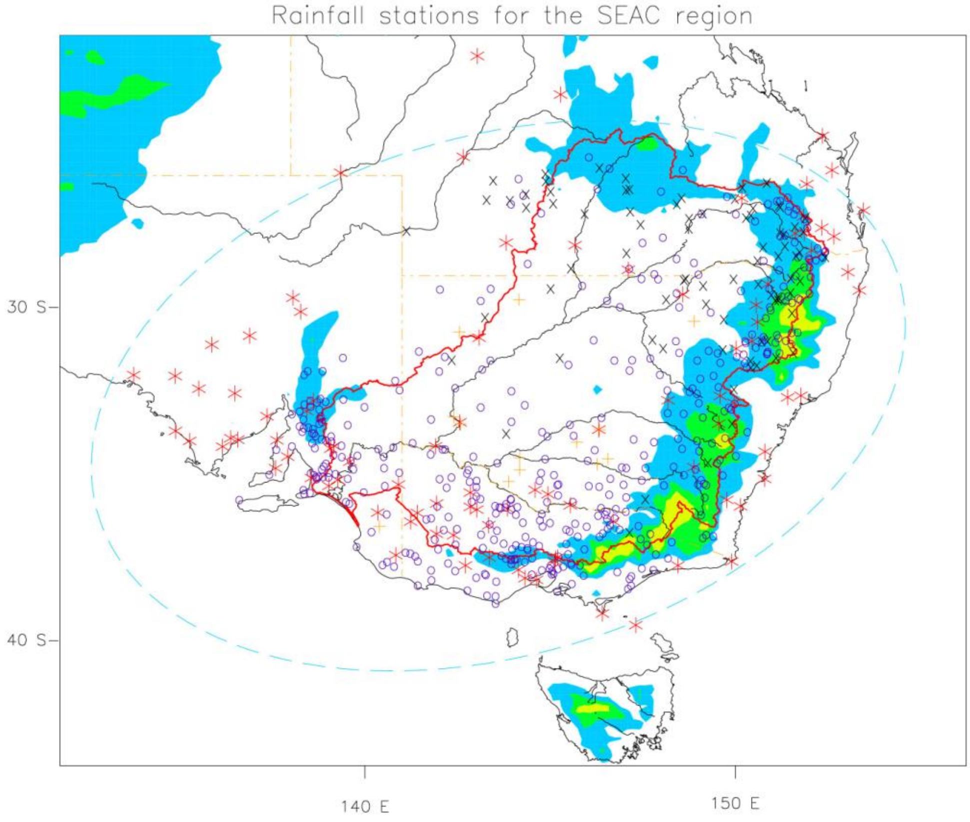


Figure 1 :*Locations of the rainfall stations chosen for the SEACI program.*

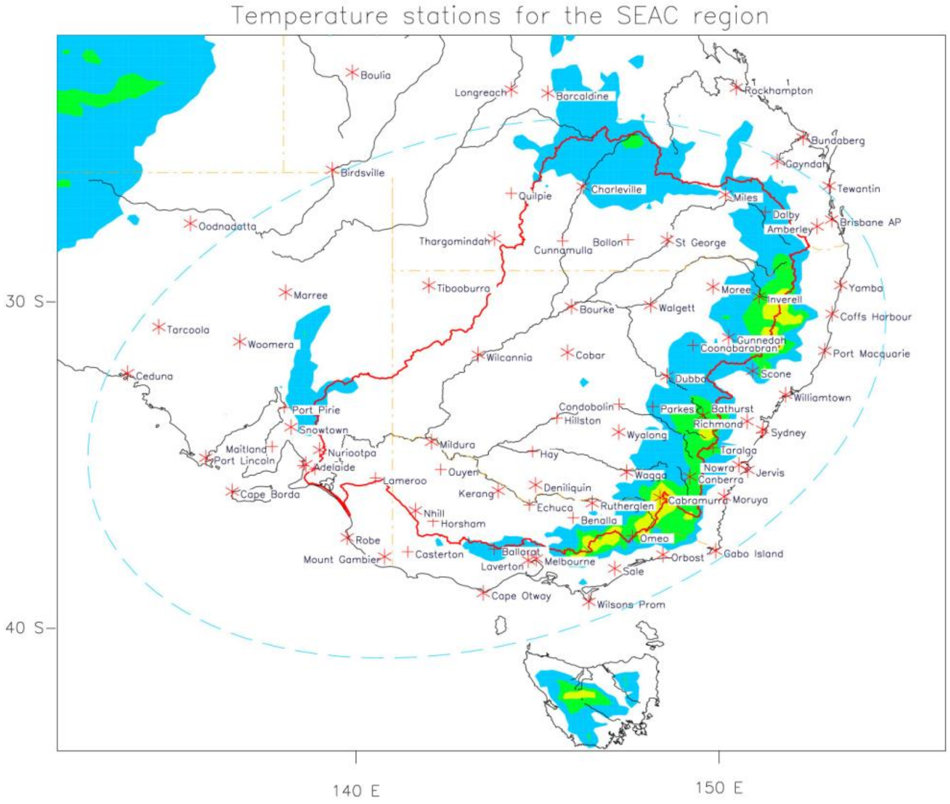


Figure 2: *Locations of the temperature stations chosen for the SEACI program.*

For daily extremes of temperature (Tmax and Tmin), only 23 stations were added to the 62 HQ stations (Fig. 2). Daily HQ temperatures (Trewin, 2001) have few observations dating back from the beginning of the 20th Century, with most starting in the 1950s. Some additional locations are the merging of neighbouring sites and hence have homogenisation issues. Others might have additional problems (site exposure or urban contamination). A complete list of the stations names, locations, temporal coverage as well as any data quality issue is provided in Appendix 2.

HQ dew point stations (Lucas et al., 2004) are only available from 1957, therefore no additional stations could be added; only 13 stations across the SEACI study region are available (Fig. 3). At each location, daily maximum, daily minimum, and 9 am dew point temperatures are available. In addition, 9 am relative humidity has been calculated; however it is based on non-homogenised 9 am air temperature at the same site and therefore is potentially problematic. A complete list of the stations names, locations and temporal coverage is provided in Appendix 3.

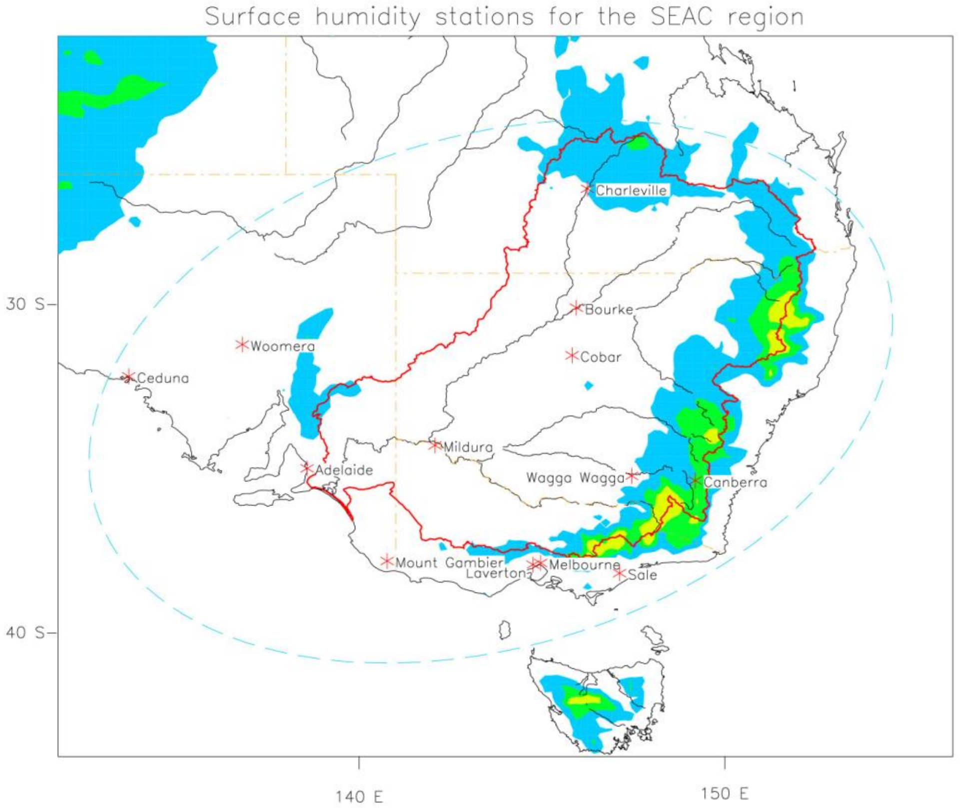
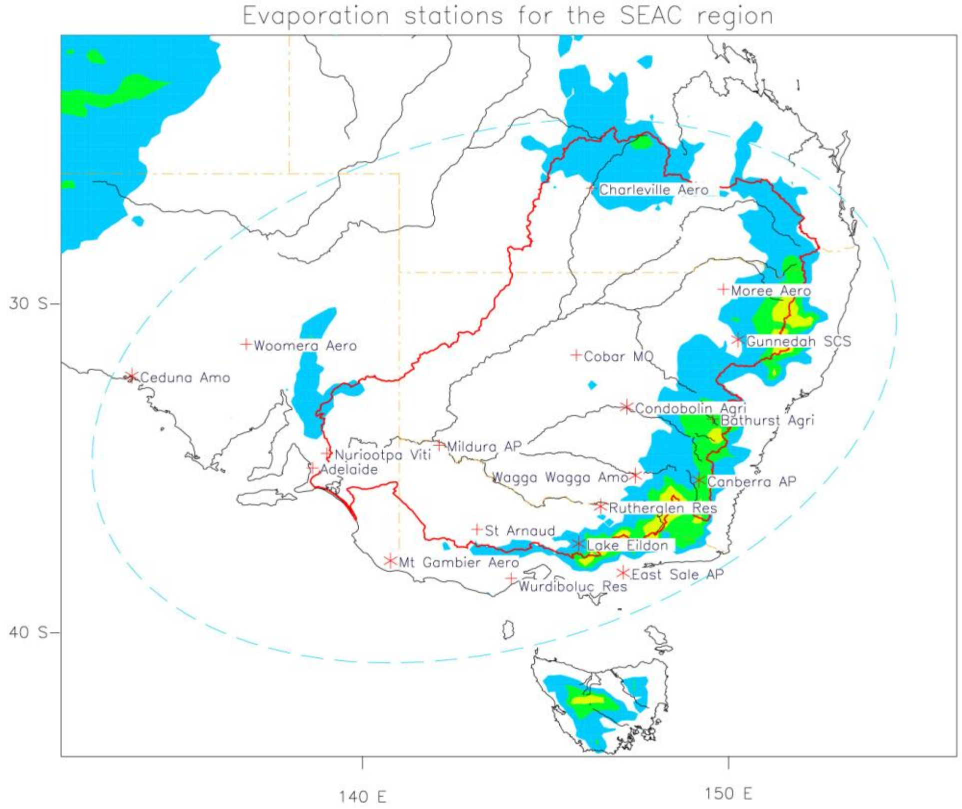


Figure 3: *Locations of the surface humidity stations chosen for the SEACI program.*

Finally, pan evaporation HQ stations have been recently assembled across Australia (Jovanovic et al., 2006) from 1975. 19 stations are scattered across the SEACI study region (Fig. 4). The BoM pan evaporation HQ dataset is a monthly dataset; we extend the quality control to daily values for the SEACI region, using monthly corrections for non-homogeneities at stations which required such correction. A complete list of the stations names, locations and temporal coverage, as well as which stations required a daily homogenisation, is provided in Appendix 4.



Characterisation of the climate of the last decade in the SEACI region

The climate in south-eastern Australia (SEA) during last decade has been extremely dry (Trewin, 2006). This dry decade has been characterised for the SEACI region using the dataset that has been assembled and additional gridded data from the National Climate Centre of the BoM have been used. The recent climatic trend in the SEA has been analysed and placed in the context of the long-term historical record.

The dry conditions from 1996 to the present are not unprecedented: one drier 10-year spell has been recorded across the region during the 1940s and another decade was nearly as dry (the so-called Federation Drought) at the beginning of the century (Fig. 5). The current situation has been exacerbated by three factors which make this recent climatic anomaly more significant in term of impacts. First, higher air temperatures due to on-going global warming have been observed. Temperatures in the SEACI region have been increasing more rapidly since 1970. The last ten years have seen warmer maximum temperatures across the SEACI region. Some regions (western Victoria and NSW) have been cooler at night and half of this variability can be explained by drier conditions.

Second, the last decade has been marked by very low inter-annual variability (the lowest on record); the absence of any year way above normal year is noticeable (2000 has been the wettest year, and was only about six per cent above the long term average). We are now seeing a total lack of wet years to compensate for dry years. The third factor of interest is that most of the rainfall trend since 1991 (72 per cent) is due to lower rainfall in autumn, an important season leading to the saturation of the soil before the harvesting of winter rainfall (Murphy and Timbal, 2007). The likelihood that the strong seasonal cycle on the rainfall decline is contributing to its severe impact on water resources and inflows requires further investigations.

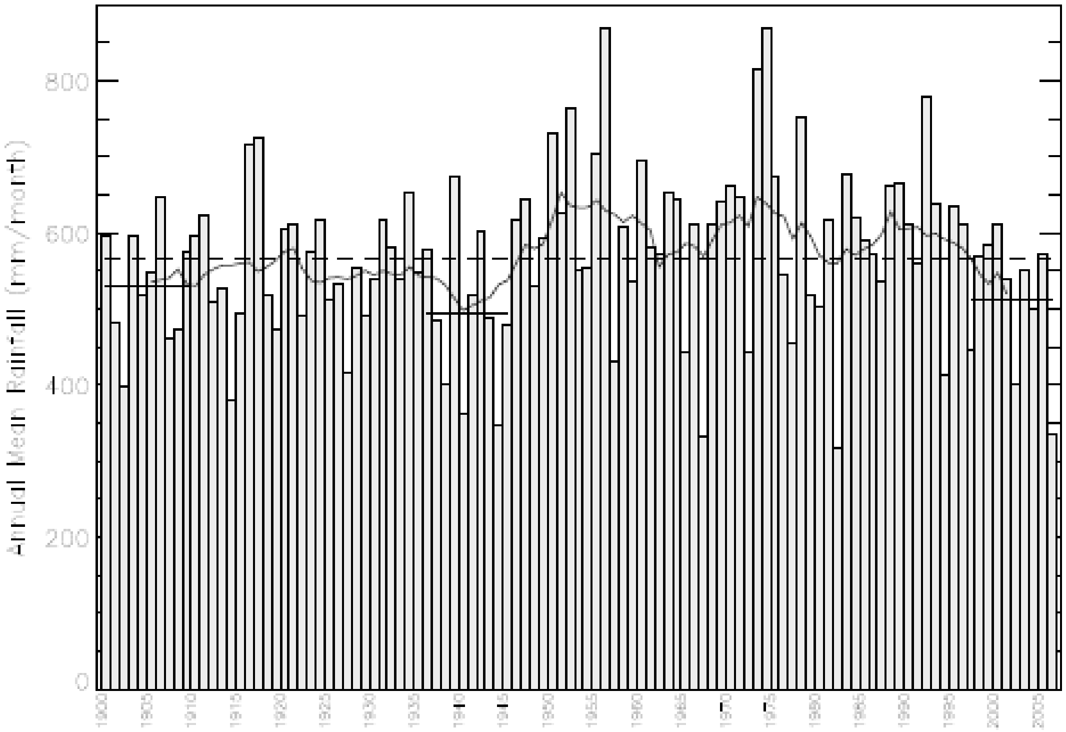


Figure 5: *Mean annual rainfall over south-eastern Australia (mainland south of 33 °S, east of 135 °E) for each year from 1900 to 2006. Also shown are the 1900–2006 mean (dashed line), the 10-year means for 1997–2006, 1900–1909 and 1936–1945 (thick, short horizontal lines) and the 11-year running mean (solid black). Units are mm.*

Large-scale mode of variability and their relation to the climate of the SEACI region

A series of indices were explored to analyse the impact of ENSO (Niño 3, Niño 4, Niño 3.4, and the SOI). All indices show similar behaviour and results are presented for Niño 4 (Western Pacific, 160 °E–150 °W) constructed using sea surface temperature (SST) anomalies from Smith and Reynolds (2004) reconstruction version 2. Similarly indices were constructed using the same SST database to explore the role of the Indian Ocean, whose main mode of variability, the Indian Ocean Dipole (IOD), has been linked to SEA (Meyer et al., 2007). One index is used for the Indonesia-Indian Equatorial Ocean (120°–130°E, 10°S–0°N) and one for the north-west shelf (NWS: 100°–130°E, 20°S–5°S). The focus here is on the eastern side of the IOD which is more likely to impact directly on SEA rainfall. Only results for the NWS are presented as both indices yield similar results. In addition, an index was built for the neighbouring Tasman Sea (150°-160°E, 40°-30°S) SSTs. Finally, for the SAM, the Marshall

(2003) SAM index was used; which is calculated from station pressure observations covering 1958–2005.

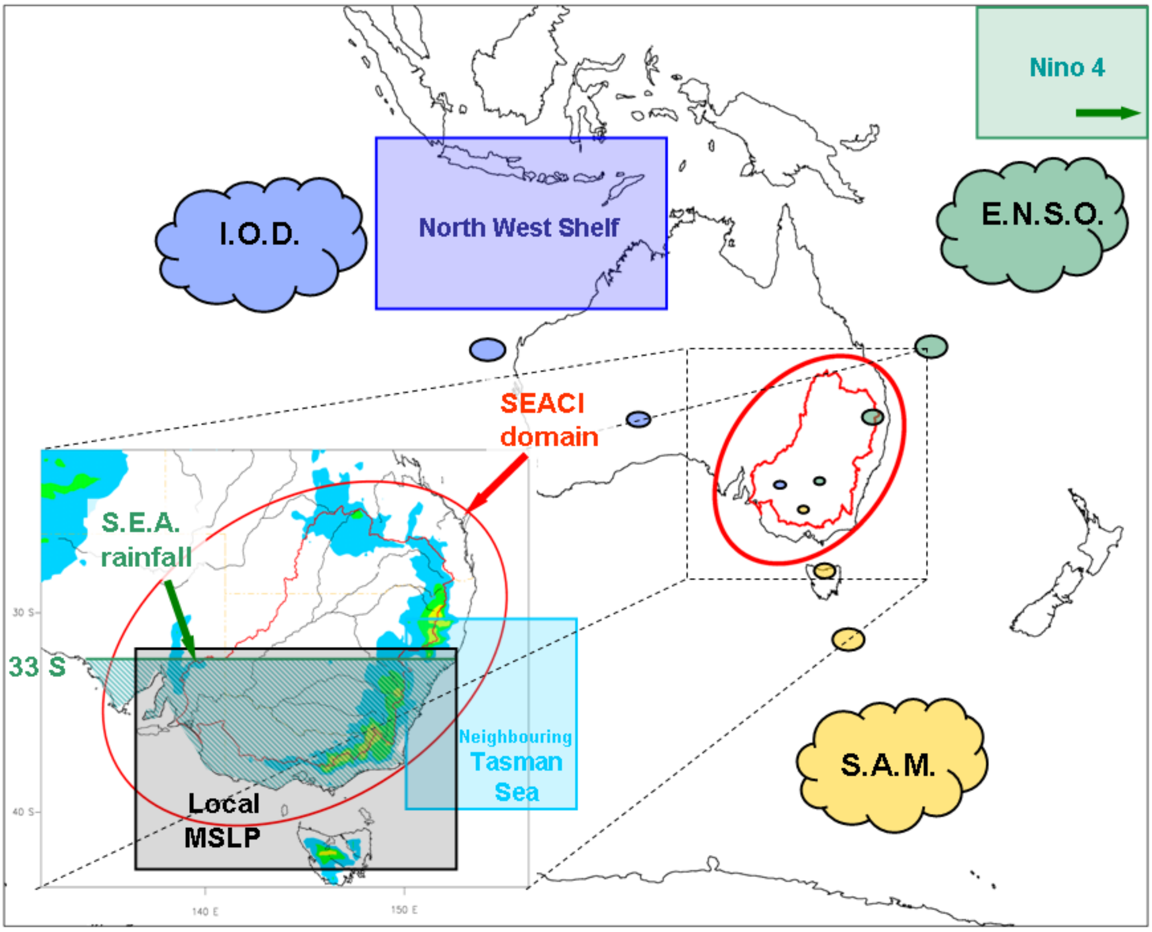


Figure 6: *Schematic of the SEACI study region, and the large-scale influences affecting the climate of the region.*

Finally, many of the influences of the climate indices in SEA come about through modulations of the atmospheric circulation. This was quantified by computing a MSLP index for SEA (from 140 °E to 150 °E and from 33 °S to 40 °S) using gridded HadSLP2 data with 5° resolution from 1850–2004 (Allan and Ansell, 2006). In order to remove this indirect influence we have calculated a time series of SEA rainfall with the time series of rainfall regressed on the MSLP time series. The rainfall residual time series is therefore uncorrelated with SEA MSLP.

Table 1: *Correlation between SEA mean Tmax, Tmin, Rainfall and a rainfall residual (with the linear relationship to mean sea level pressure removed), and a range of climate indices for the four calendar seasons. The climate indices are discussed in the text. Note: Red figures indicate significance above the 99 per cent level and bold figures above the 90 per cent level.*

Autumn	Tmax	Tmin	Rain	R-f(P)
MSLP SEA	**0.40**	**-0.24**	**-0.29**	
Niño 4	0.16	**-0.26**	-0.16	-0.06
NWS	**0.28**	0.11	0.07	**0.19**
SAM	-0.06	-0.02	-0.02	0.09
Tasman	**0.32**	**0.49**	**0.25**	**0.27**

Winter	Tmax	Tmin	Rain	R-f(P)
MSLP SEA	**0.54**	**-0.44**	**-0.74**	
Niño 4	0.19	-0.16	**-0.20**	-0.06
NWS	0.08	**0.41**	**0.30**	**0.32**
SAM	-0.01	**-0.31**	**-0.27**	0.17
Tasman	**0.39**	**0.30**	0.07	**0.22**

Spring	Tmax	Tmin	Rain	R-f(P)
MSLP SEA	**0.46**	**0.29**	**-0.39**	
Niño 4	**0.33**	-0.11	**-0.37**	**-0.28**
NWS	0.00	**0.34**	**0.26**	**0.19**
SAM	-0.20	**0.28**	**0.31**	**0.47**
Tasman	**0.40**	**0.60**	0.16	**0.22**

Summer	Tmax	Tmin	Rain	R-f(P)
MSLP SEA	0.14	**0.34**	0.14	
Niño 4	0.11	-0.07	**-0.18**	**-0.23**
NWS	**0.24**	0.19	-0.09	-0.13
SAM	0.02	**0.30**	**0.31**	**0.27**
Tasman	**0.43**	**0.55**	**0.19**	**0.19**

Significance of the correlations obtained was assessed using the method described by Power et al. (1998). The method takes into account the autocorrelations of the time series. Generally the autocorrelations at one-month lag were very small for most indices (only for the SST-based indices were they greater than 0.1), and so the impact of these autocorrelations was minimal. When we talk of significant correlations we mean that the correlations are deemed to be significantly different from zero at the 90 per cent significance level (in bold in Table 1) and very significant (at the 99 per cent level, in red in the following table).

The main findings are:

1. Local MSLP has the greatest influence of all indices (except in summer when it is mostly negligible (except for Tmin) and will not be discussed further). Local MSLP has a negative influence on rainfall which is strongest in the heart of winter (e.g. rainfall is associated with low pressure systems) and a positive influence on maximum temperature (e.g. higher temperature associated with highs). The influence on minimum temperature is more complex and swaps sign between autumn/winter, when high MSLP means clear skies and colder night-time temperatures, and spring/summer when the relationship becomes positive due to the influence of Tmax (Power *et al.*, 1999).

2. ENSO-related correlations are at the strongest in spring and generally highest for rainfall and Tmax. The highest correlation is -0.39 between Niño 3.4 and SEA-mean rainfall in spring. It reaches 0.50 with the SOI, but still only explains 25 per cent of variance. This confirms that SEA is not the Australian region the most affected by ENSO (Nicholls, 1989). The strong relationship with rainfall in spring is strongly reduced when the influence of local MSLP is removed, thus confirming that the influence of ENSO on SEA rainfall is through large-scale circulation changes.

3. Indian Ocean SSTs are related to rainfall and Tmin in winter and in spring as well, but the signal is weaker. Interestingly the relationship with rainfall is only reduced, and slightly, in spring when the influence of local MSLP is removed, but it remains unchanged in winter and in autumn it increases and becomes significant. It suggests that the influence of the warm SSTs along the North-West coast of Australia is felt in SEA by other mechanisms than circulation changes, e.g. moisture fluxes.

4. The Southern Annular Mode (SAM) index correlates significantly in all seasons except autumn. The SAM modulates SEA rainfall in winter where the negative correlation indicates that the southward contraction of storm track leads to less rain. The opposite is true in spring and summer where there is more rain with southward storm track (Hendon et al., 2007). The signature for Tmin is similar and there is no influence on Tmax. The impact of the SAM is expected to come about through circulation changes. However, when the effect of MSLP is removed the correlation between the SAM and SEA rainfall in winter changes sign, and in spring it is much stronger, thus suggesting that the direct influence of SAM on SEA rainfall is stronger due to some changes in the flow but is reduced by the concomitant impact on regional MSLP.

5. The strongest influence of neighbouring Tasman Sea SSTs is seen on temperature: Tmax in winter and Tmin in spring-summer-autumn. The only significant correlation with rainfall is in autumn (0.25). Interestingly, when the impact of MSLP is removed, the relationship with rainfall is always stronger, albeit still modest, and becomes significant in all seasons.

From these relationships between SEA climate and large-scale indices, it is hard to explain the step change of rainfall in SEA which has occurred in autumn. None of the climate indices have a strong relationship in that season and the only significant ones (the neighbouring Tasman Sea with rainfall and NWS with rainfall residual) are unlikely to explain the rainfall decline since both indices have been tending upward. At this stage, it appears that the rainfall decline can only be explained as part of a response to an increase in local MSLP. What causes the MSLP increase remains to be fully defined.

However, it is possible that the chosen domain encompasses several influences which might differ from one part of the region to another. In order to investigate this further, we have to broaden the perspective and look at the rainfall in four areas included within the SEACI domain (red ellipse in Fig. 1) matching those uncovered through rotated EOF analysis of

Australian rainfall by Drosdowsky and Chambers (2001). We have calculated the average monthly-mean rainfall for two stations in each region that capture the spatial variability of these rainfall patterns. High quality rainfall stations were used. Maps of the correlation between these time series and the monthly gridded HQ rainfall analyses over the period 1948–2005 are shown in Figure 6. Areas where the correlations explain more than 20 per cent of the total variance are shaded and show the main centres of action of these patterns of rainfall variability. They match very well four of the rotated EOFs from Drosdowsky and Chambers (2001): number 1 (Fig. 6 top left based on rainfall at Peak Hill and Bingara), number 2 (Fig. 6 top right, based on rainfall at Murray-Bridge and Orroroo), number 5 (Fig. 6 bottom left, based on rainfall at Meredith and Yan Yean) and number 8 (Fig. 6 bottom right, based on rainfall at Thargomindah and White cliffs).

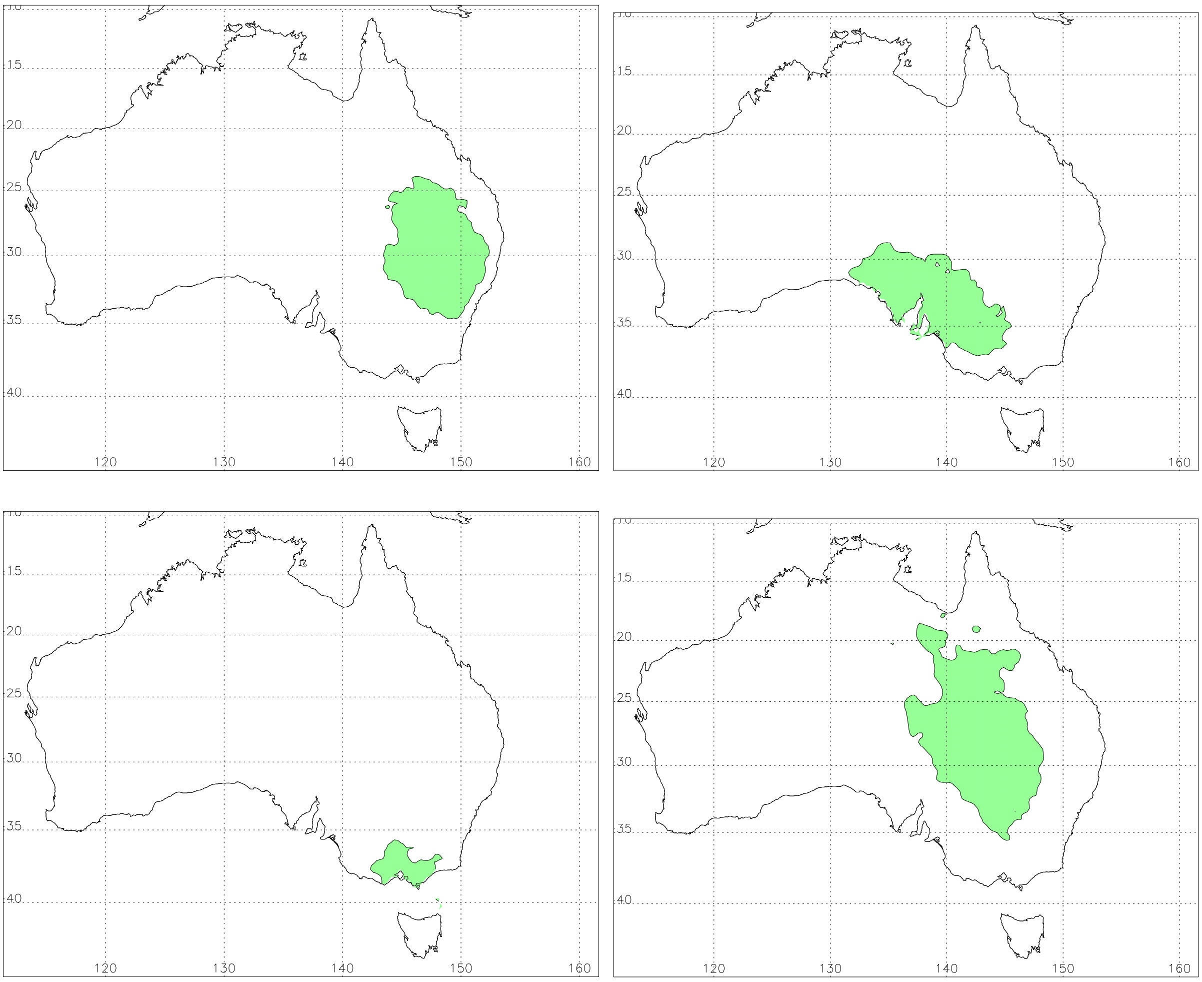


Figure 6: *Four rainfall patterns covering SEA (see text for details on their calculation) and referred to in the following analysis as: Eastern (top left), North-West Cloud Band (NWCB) (top right), Victoria (bottom left), Central (bottom right).*

The four patterns generally do not overlap and cover most of the SEACI region. The mean monthly rainfall of each pair of stations was averaged to give a time series of a regional rainfall index. Some interesting regional features emerge (Table 2). As for rainfall across the SEA, the relationship with local MSLP (using rectangular boxes depicted in Fig. 6 for each rainfall sub-region) was remove from the rainfall series and compared with the four major climate indices for all seasons except summer when the rainfall-MSLP relationship is non-existent (Table 3).

Table 2: *Correlation between rainfalls for four regions in the SEACI domain and a range of climate indices for the four calendar seasons. Note: red figures indicate significance above the 99 per cent level and bold figures above the 90 per cent level.*

Autumn	NWCB	Victoria	Eastern	Central
MSLP SEA	**-0.43**	**-0.39**	**-0.26**	**-0.36**
Niño 4	**-0.35**	**-0.30**	-0.16	**-0.37**
NWS	0.04	-0.19	0.08	-0.16
SAM	0.04	-0.01	-0.01	0.05
Tasman	0.18	0.08	0.21	0.21

Winter	NWCB	Victoria	Eastern	Central
MSLP SEA	**-0.68**	**-0.45**	**-0.31**	**-0.33**
Niño 4	0.05	-0.15	**-0.46**	**-0.29**
NWS	**0.35**	0.09	**0.27**	**0.34**
SAM	-0.13	**-0.30**	0.14	0.13
Tasman	0.15	-0.12	0.19	**0.29**

Spring	NWCB	Victoria	Eastern	Central
MSLP SEA	**-0.28**	**-0.33**	-0.06	**-0.25**
Niño 4	-0.14	**-0.45**	**-0.46**	**-0.43**
NWS	0.07	0.05	0.20	0.16
SAM	0.18	0.13	**0.33**	**0.29**
Tasman	0.04	-0.17	**0.31**	**0.24**

Summer	NWCB	Victoria	Eastern	Central
MSLP SEA	0.03	0.14	-0.17	-0.09
Niño 4	0.03	-0.04	-0.15	**-0.33**
NWS	-0.06	-0.11	0.00	-0.18
SAM	0.17	0.16	0.22	**0.29**
Tasman	0.09	0.08	**0.39**	0.18

Table 3: *Correlation between a rainfall residual (with the relationship to mean sea level pressure removed) for four regions in the SEACI area and a range of climate indices for autumn, winter and spring. Note: red figures indicate significance above the 99 per cent level and bold figures above the 90 per cent level.*

Autumn	NWCB	Victoria	Eastern	Central
Niño 4	-0.17	-0.21	-0.02	-0.19
NWS	**0.26**	0.00	0.24	-0.02
SAM	0.19	0.14	0.08	0.16
Tasman	0.13	0.08	0.21	0.16

Winter	NWCB	Victoria	Eastern	Central
Niño 4	**0.31**	-0.05	**-0.39**	**-0.24**
NWS	**0.26**	0.02	0.23	**0.27**
SAM	**0.28**	-0.05	**0.33**	**0.33**
Tasman	**0.28**	-0.04	**0.25**	**0.28**

Spring	NWCB	Victoria	Eastern	Central
Niño 4	-0.02	**-0.34**	**-0.44**	**-0.29**
NWS	-0.02	0.00	0.17	0.10
SAM	0.25	**0.30**	**0.35**	**0.34**
Tasman	0.13	0.08	0.21	0.16

The important regional variations which add information from the previous SEA averages are:

- The relationship with local MSLP is strongest in the southern and western regions (particularly in winter).

- The influence of Niño4 SSTs is strong in eastern and central regions but disappears further west in winter. In autumn the picture is rather different, with stronger correlations away from the eastern region. While the relationship with the eastern regions in winter remains significant once the influence of local MSLP is removed, it is not so in autumn with the western regions. This suggests two different mechanisms for the influence of NIÑO4 on the SEACI study region: a direct influence with the north-eastern part of the domain in winter (possibly due to moisture fluxes) and an indirect relationship with the south-western part of the study region in autumn (probably due to circulation changes).

- The influence of the IOD is weak everywhere in autumn, but moderate in winter outside the southern region. However once the relationship with local MSLP is removed (increasing correlation in autumn by about 0.2 and decreasing them in winter by about 0.1) the influence is very similar in both seasons (apart in the central region). The seasonal differences appear to be due to circulation changes which differ in both seasons.

- The negative influence of SAM in winter is limited to the south-west of the domain and changes sign further north (in agreement with Hendon et al., 2007). As per the SEA average, correlations increase everywhere once the MSLP influence is removed. No significant correlations are seen in autumn.

- The influence of the NTS is felt mostly outside the MSLP influence and is moderate in winter everywhere apart of the Southern region. In autumn, it is also not impacted by the MSLP relationship but it is insignificant everywhere.

Conclusions

As part of this project, datasets are now available for SEACI-wide station data of daily values of rainfall, temperature, humidity and pan evaporation. The dataset combines stations of the highest possible quality with additional stations when necessary to enhance spatial coverage. A analysis of long-term rainfall trends and variability, based on this dataset, shows that most of SEA south of 33 °S has had rainfall for 1997-2006 in the lowest 10 per cent on record. Only one previous 10-year period had average rainfall over SEA less than the current average (1935–1945). Most of the rainfall decline in SEA has come in the autumn season (72 per cent). In addition, year-to-year variations in annual mean rainfalls over SEA have been the lowest on record. Furthermore, the recent dry period has been compounded by an underlying warming trend.

The main driver of SEA rainfall is the surface air pressure. MSLP has been trending toward higher values and the relationship with lower rainfall is strong in most seasons and explains the rainfall decline. Over the entire SEA region the step change in autumn rainfall does not appear to be clearly related to a single mode of large-scale variability; correlations are usually weak to moderate. Several forcings inter-play and their importance differs from one sub-region to another. Significant negative correlations with Niño4 SSTs are apparent in autumn for the south-western and central part of the domain, once additional regions are used within the SEACI domain of interest. It is interesting to compare this results with the pattern of the rainfall decline in the SEA since 1996 (Trewin, 2006) which peaks in the south-west of the region as well. It suggests the possibility that the warming of the tropical central Pacific (Niño4 region), not necessarily related to a trend in ENSO but simply the global warming of the ocean, together with the rises of MSLP above SEA have contributed to the autumn rainfall decline. No attempt is made here to explain the causes of the MSLP increase. But it is reasonable to suggest in light of these results that the inter-play between these modes of variability and the local MSLP are important to explain the regional rainfall decline.

Acknowledgement

This work was funded by the South Eastern Australia Climate Initiative.

Outputs from this project

Publications:

Murphy, B.F. and B. Timbal, 2007: A review of recent climate variability and climate change in south eastern Australia. *Int. J. Clim. (*submitted).

Timbal, B. and B.F. Murphy, 2007: Observed climate change in South-East of Australia and its relation to large-scale modes of variability. *BMRC Research Letter (*submitted).

Datasets:

Daily climatic data are available for rainfall, temperature (min and max), dew point (min, max and 9am) and pan-evaporation for the SEACI region (see annexes for stations list).

References

Allan, R. and T. Ansell, 2006: A new globally complete monthly historical gridded Mean Sea level Pressure dataset (HadSLP2): 1850-2004. *J. Climate,* **19**: 5816-5842.

Drosdowsky W. and L.E. Chambers, 2001: Near global sea surface temperature anomalies as predictors of Australian seasonal rainfall. *J. Climate*, **14**, 1677-1687.

Hendon, H.H., D.W.J. Thompson, and M.C. Wheeler, 2007: Australian rainfall and surface temperature variations associated with the Southern Annular Mode. *J. Climate,* in press.

Jovanovic, B., Jones, D. A., and Collins, D., 2006: A High Quality Monthly Pan-Evaporation Dataset for Australia. *Climatic Change* **87**: 3-4.

Lavery, B., Kariko, A. and Nicholls, N. 1992: A historical rainfall data set for Australia. *Australian Meteorological Magazine*, **40**: 33-39.

Lavery, B., Joung, G. and Nicholls, N. 1997: An extended high-quality historical rainfall dataset for Australia. *Australian Meteorological Magazine*, **46**: 27-38.

Lucas, C., Trewin, B., and Nicholls, N., 2004: Development of an historical humidity database for Australia. Abstracts for 16th Australia New Zealand Climate Forum, Lorne, 8-10 November 2004, p 59.

Marshall, G. J. 2003: Trends in the Southern Annular Mode from observations and reanalyses. *J. Climate,* **16**: 4134-4143.

Meyers, G., McIntosh P., Pigot, L. and M. Pook, 2007: The years of El Niño, La Niña and interactions with the tropical Indian Ocean. *J. Climate* (in press).

Murphy, B.F. and B. Timbal, 2007: A review of recent climate variability and climate change in south eastern Australia. *Int. J. Clim.* (submitted).

Nicholls, N., 1989: Sea surface temperatures and Australian winter rainfall. *J. Climate*, **2**: 965-973.

Power S, Tseitkin F., Mehta V., Lavery B., Torook S. and N. Holbrook, 1999: Decadal climate variability in Australia during the twentieth century. *Int. J. Clim.,* **19**: 169-184.

Smith, T.M. and R.W. Reynolds, 2004: Improved Extended Reconstruction of SST (1854-1997). *J. Climate*, **17**: 2466-2477.

Trewin, B.C., 2001: *Extreme temperature events in Australia*. PhD Thesis, School of Earth Sciences, University of Melbourne, Australia

Trewin, B.C., 2006: An exceptionally dry decade in parts of southern and eastern Australia October 1996 - September 2006. *Special Climate Statement* **No. 9**, Australian National Climate Centre, 9 pp.

Appendix 1: list of rainfall stations

In total 585 stations have been selected within the SEACI climatic region. The full list is not provided here but some general information about the data quality. All stations are available on request:

Notes

There are 95 HQ stations in the SEACI region

Rainfall high quality dataset was initially put together by B. Lavery et al. (1992, Aust. Met. Mag.) The dataset has been updated by D. Collins NCC, 2006, available online at:
ftp://ftp.bom.gov.au/anon/home/ncc/www/change/HQdailyR/HQdailyR_info.pdf
A known issue with HQ rainfall station is the existence of unreported accumulations. See: Viney and Bates, It never rains on Sunday: the prevalence and implications of untagged mutli-day rainfall accumulations in the Australian high quality data set *Int. J. of Climatol.*, 24: 1171–1192 (2004).

Additional stations:

Quality = 1 (395 stations): These stations have <5 per cent missing data since 1996, < 3 per cent and no missing months.

Quality = 2 (15 stations): These stations are approaching the Q1 thresholds and fill gaps in the coverage.

Quality = 3 (80 stations): These stations meet the Q1 standard (5 per cent and 3 per cent) but have a low percentage (<20 per cent) of small rainfall events (less than 2mm). This suggests bad observing practices and is a concern for the overall quality at the site.

Appendix 2: list of temperature stations

Location	Station Id	Lon. (E)	Lat. (S)	Start Date	End Date	Quality	Known quality issue
adelaide	23090	138.62	-34.92	1887	Open	HQ	
adelaide airport	23034	138.52	-34.95	1955	Open	1	Urban affected
amberley	40004	152.71	-27.63	1941	Open	HQ	
ballarat	89002	143.79	-37.51	1908	Open	1	Site has moved; not homogeni
barcaldine	36007	145.29	-23.55	1957	Open	HQ	
bathurst	63005	149.56	-33.43	1908	Open	HQ	
benalla	82002	145.97	-36.55	1882	Open	1	Site exposure is not good
birdsville	38002	139.35	-25.90	1957	Open	HQ	
bollon	44010	147.48	-28.03	1885	Open	1	Some missing data
boulia	38003	139.90	-22.91	1949	Open	HQ	
bourke	48013	145.94	-30.09	1957	Open	HQ	
brisbaneap	40223	153.11	-27.42	1949	Open	HQ	
bundaberg	39128	152.32	-24.91	1959	Open	HQ	
cabramurra	72091	148.38	-35.94	1962	Open	HQ	
canberra	70014	149.20	-35.30	1939	Open	HQ	
capeborda	22801	136.59	-35.75	1957	Open	HQ	
capeotway	90015	143.51	-38.86	1957	Open	HQ	
casterton	90135	141.41	-37.59	1956	Open	1	
ceduna	18012	133.71	-32.13	1939	Open	HQ	
charleville	44021	146.26	-26.41	1942	Open	HQ	
cobar	48027	145.83	-31.49	1957	Open	HQ	
coffsharbour	59040	153.12	-30.31	1943	Open	HQ	
condobolin	50052	147.23	-33.07	1965	Open	1	Many missing data prior to 19
coonabarabran	64008	149.27	-31.27	1879	Open	1	Site moved in 1994
cunnamulla	44026	145.68	-28.07	1879	Open	1	Reasonable
dalby	41522	151.26	-27.18	1958	Open	1	Move from city to airport
deniliquin	74128	144.95	-35.55	1949	Open	HQ	
dubbo	65012	148.57	-32.21	1957	Open	HQ	
echuca	80015	144.76	-36.16	1957	Open	1	
gaboisland	84016	149.91	-37.57	1957	Open	HQ	
gayndah	39039	151.61	-25.63	1957	Open	HQ	
gunnedah	55024	150.27	-31.03	1959	Open	HQ	
hay	75031	144.85	-34.52	1877	Open	1	
hillston	75032	145.52	-33.49	1881	Open	1	
horsham	79023	142.11	-36.65	1873	Open	1	
inverell	56017	151.11	-29.78	1957	Open	HQ	
jervis	68034	150.80	-35.09	1957	Open	HQ	
kerang	80023	143.92	-35.73	1957	Open	HQ	
lameroo	25509	140.52	-35.33	1899	Open	1	
laverton	87031	144.75	-37.86	1943	Open	HQ	
longreach	36031	144.28	-23.44	1957	Open	HQ	
maitland	22008	137.67	-34.37	1879	Open	1	
marree	17031	138.06	-29.65	1957	Open	HQ	
melbourne	86071	144.97	-37.81	1855	Open	HQ	
mildura	76031	142.08	-34.23	1946	Open	HQ	
miles	42023	150.18	-26.66	1957	Open	HQ	

moree	53048	149.84	-29.48	1879	Open	HQ	
moruya	69018	150.15	-35.91	1921	Open	HQ	
mount barker	23733	138.85	-35.06	1861	Open	1	Bad site prior to 1997.
mountgambier	26021	140.79	-37.75	1942	Open	HQ	
nhill	78031	141.64	-36.34	1951	Open	HQ	
nowra	68076	150.55	-34.94	1955	Open	HQ	
nuriootpa	23321	139.00	-34.48	1957	Open	HQ	
omeo	83025	147.60	-37.10	1879	Open	1	
oodnadatta	17114	135.44	-27.54	1940	Open	HQ	
orbost	84030	148.46	-37.69	1957	Open	HQ	
ouyen	76047	142.32	-35.07	1911	Open	1	
parkes	65026	148.16	-33.14	1958	Open	1	Site exposure is not good
port pirie	21043	138.01	-33.17	1877	Open	1	Site exposure is not good
portlincoln	18070	135.86	-34.72	1957	Open	HQ	
portmacquarie	60026	152.92	-31.44	1921	Open	HQ	
quilpie	45015	144.26	-26.61	1958	Open	1	
richmond_nsw	67105	150.78	-33.60	1939	Open	HQ	
robe	26026	139.76	-37.16	1957	Open	HQ	
rockhampton	39083	150.48	-23.38	1939	Open	HQ	
rutherglen	82039	146.51	-36.11	1957	Open	HQ	
sale	85072	147.13	-38.11	1945	Open	HQ	
scone	61089	150.93	-32.06	1959	Open	HQ	
snowtown	21046	138.21	-33.78	1958	Open	HQ	
stgeorge	43034	148.58	-28.04	1957	Open	HQ	
sydney	66062	151.21	-33.86	1859	Open	HQ	
sydney airport	66037	151.17	-33.94	1939	Open	1	Urban affected site
taralga	70080	149.82	-34.40	1882	Open	1	Missing data on Sundays
tarcoola	16044	134.57	-30.71	1950	Open	HQ	
tewantin	40264	153.04	-26.39	1957	Open	HQ	
thargomindah	45017	143.82	-28.00	1957	Open	HQ	
tibooburra	46037	142.01	-29.44	1921	Open	HQ	
wagga	72150	147.46	-35.16	1942	Open	HQ	
walgett	52088	148.12	-30.04	1957	Open	HQ	
wilcannia	46043	143.37	-31.56	1957	Open	HQ	
williamtown	61078	151.84	-32.79	1942	Open	HQ	
wilsonsprom	85096	146.42	-39.13	1957	Open	HQ	
woomera	16001	136.80	-31.16	1949	Open	HQ	
wyalong	73054	147.24	-33.93	1959	Open	HQ	
yamba	58012	153.36	-29.43	1921	Open	HQ	

Notes: There are 62 HQ stations in the SEACI region

Temperature HQ dataset was initially put together by B. Trewin (2001, PhD thesis, Melbourne Uni.) The dataset has been updated by D. Collins NCC, 2006, available online at:
ftp://ftp.bom.gov.au/anon/home/ncc/www/change/HQdailyT/HQdailyT_info.pdf

Additional stations (23)

Quality = 1 for stations with few missing data since 1958 but which fail test for the HQ network
Some locations are the merging of neighbouring sites and hence have homogenisation issues
Additional problems if any are noted for individual station

Appendix 3: list of surface humidity stations

Location	Station Id	Lon. (E)	Lat. (S)	Start Date	End Date	Quality	Footnote
adelaide	23000	138.58	-34.93	1957	2003	HQ	
bourke	48239	145.95	-30.04	1957	2003	HQ	F1
canberra	70014	149.20	-35.30	1957	2003	HQ	
ceduna	18206	133.70	-32.13	1957	2003	HQ	
charleville	44021	146.25	-26.42	1957	2003	HQ	
cobar	48027	145.83	-31.49	1957	2003	HQ	
laverton	87031	144.76	-37.86	1957	2003	HQ	
melbourne	86071	144.97	-37.81	1957	2003	HQ	
mildura	76031	142.08	-34.23	1957	2003	HQ	
mountgambier	26021	140.77	-37.75	1957	2003	HQ	
sale	85072	147.13	-38.12	1957	2003	HQ	
wagga	72150	147.46	-35.16	1957	2003	HQ	
woomera	16001	136.81	-31.16	1957	2003	HQ	

Notes:

Dew point high quality (HQ) dataset was put together by C. Lucas (2006, ANZ Clim. For., Canberra). The variables are:

- Maximum – depoint dTmax
- Minimum – dewpoint dTmin
- 9 am dew point (taken between 9-10 am depending on Daylight Savings
- 9 am relative humidity RH based on non-homogenised 9 am temperature

F1 has a lot of missing data (20 per cent).

Appendix 4: list of pan evaporation stations

Location	Station Id	Lon. (E)	Lat. (S)	Start Date	End Date	Quality
adelaide	23090	138.62	-34.92	1975	31/12/2005	1
bathurst_agri	63005	149.56	-33.43	1975	31/12/2005	1
canberra_ap	70014	149.20	-35.30	1975	31/12/2005	HQ
ceduna_amo	18206	133.70	-32.13	1975	31/12/2005	HQ
charleville_aero	44021	146.25	-26.42	1975	31/12/2005	1
cobar_mo	48027	145.83	-31.49	1975	31/12/2005	1
condobolin_agri	50052	147.23	-33.07	1975	31/12/2005	HQ
east_sale_ap	85027	147.13	-38.12	1975	31/12/2005	HQ
gunnedah_scs	55024	150.27	-31.03	1975	31/12/2005	HQ
lake_eildon	88023	145.91	-37.23	1975	31/12/2005	HQ
mildura_ap	76031	142.08	-34.23	1975	31/12/2005	1
moree_aero	53115	149.85	-29.49	1975	31/12/2005	1
mt_gambier_aero	26021	140.77	-37.75	1975	31/12/2005	HQ
nuriootpa_viti	23373	139.01	-34.48	1975	31/12/2005	1
rutherglen_res	82039	146.51	-36.10	1975	31/12/2005	HQ
st_arnaud(tottington)	79079	143.12	-36.79	1975	31/08/2005	1
wagga_wagga_amo	72150	147.46	-35.16	1975	31/12/2005	HQ
woomera_aero	16001	136.81	-31.16	1975	31/12/2005	1
wurdiboluc_res	87126	144.05	-38.28	1975	31/10/2005	1

Notes:
Pan-evaporation high quality (HQ) dataset was put together by B. Jovanovic et al. (2006)
Daily data were generated using monthly homogenisation coefficients

Quality = HQ– no corrections were needed and hence the daily values are of the highest quality

Quality = 1 correction were needed and monthly homogenisation coefficient were applied to daily values