PROJECT 1.2: SOUTH-WEST WESTERN AUSTRALIA'S REGIONAL SURFACE CLIMATE AND WEATHER SYSTEMS

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Objectives

- To determine if seasonal rainfall across the wider South-West is showing new trends in totals or shifts in intensity.
- To determine whether there has been a shift to a new weather regime in recent years.
- To determine whether observed changes are likely to continue into the future.
- To place the current multi-decade rainfall decline in the context of the last few 100 years.

Planned Outcomes

To analyse rainfall totals and intensities in the South-West during the summer and spring, and determine whether there are any trends. An update of the analysis of the winter season will be included also. In addition, detail the different weather systems (identified by a new classification scheme) for summer and spring, and report on how the frequency of these systems have changed in time.

Key Research Findings

- The data quality from rainfall recording stations formerly noted for their high-quality and long-term records have been re-assessed. Some stations with long-term, high-quality data have had reductions in quality in recent years for a range of reasons, including the consolidation of farms. This information has fed into Project 1.4.
- Annual average rainfall declined in south-west Western Australia in the late 1960s and has not recovered since. A further shift to lower rainfall was identified at approximately the year 2000. The early decline was associated with a decrease in the number of days on which a winter deep low pressure system influenced the region. The recent decline was not associated with a continuing decrease in the number of deep low pressure systems, but rather had a strong contribution from an increase in the number of days when a high pressure system influences the region.
- Recent years have also seen extremely high values of winter mean sea-level pressure over SWWA. Both the increased pressures and increased daily occurrence of high pressure systems are as projected for the end of this century by climate models forced with increasing levels of atmospheric greenhouse gases. The magnitudes of the changes expressed by most models suggest that the recent high values might be expected to continue and possibly amplify.
- The recent large decline in rainfall in the late 1960s in May to July has persisted and expanded spatially. Both trends and percentage change were analysed to explore this signal. Trends reveal that regions where rainfall did not decline in the late 1960s are now seeing a decline in early winter, whilst the percentage change also suggested a strengthening signal in regions already drying (the far south-west and wheatbelt), a signal that is not so clear using trend analysis.
- The interannual variability in the far south-west continues to decline. Trends in the 95th percentile rainfall were generally weak, except along the south coast since 1970 and at Manjimup since 1950. The signal at Manjimup which shows a weakening of the decreasing trend in the extreme rainfall between the 1950-2007 period and the 1970-2007 period supports the findings in Milestone

1.2.1 that recent declines are not associated with a further decrease in the daily occurrence of deep low pressure systems.

- In the summer half year there were minimal trends from both 1950 and 1970 except inland and along the south coast where increases were seen in both totals and, as summer rainfall is dominated by extreme events, extremes.
- Analysis of 'standard' seasons was found to potentially 'hide' important information, as found by the analysis of the spring and 'late winter' (August to October) trends. There were only weak trends from 1950, but some stronger trends from 1970 in late winter: increases at Manjimup and Nyerilup and decreases at Peppermint Grove. The map of spring trends showed decreases everywhere. Examining the decadal variability by month revealed that rainfall in August and September had been increasing, but decreasing in October and November.

Summary of new linkages to other IOCI3 Project

The findings from the work done in analysing the data quality at stations across the south west for the study of extremes was used in Project 1.4.

Summary of any new research opportunities that have arisen

A research project for Managing Climate Variability (McIntosh, 2008) led to an examination of a number of different methods to identify frontal systems that bring rainfall to the wheat belt in winter, resulting in a conference presentation (Hope et al. 2009, 9ICSHMO) and an article in preparation.

Alterations to research plans

Introduce an analysis of temperatures for the summer synoptic analysis.

Due to a growing understanding of the relevant questions for the region, no longer will a new method of synoptic classification be developed for autumn, but the synoptic systems during spring will be explored.

Next steps planned

Finalise work on shifts in intensities and the comparison of frontal recognition. Continue to research the drivers of summer-time temperature to best produce a relevant synoptic classification method. Start to develop a method of classifying the synoptic systems in spring.

Publications

Peer-reviewed publications

Hope, P. and C.J. Ganter, 2010: Recent and projected rainfall trends in south-west Australia and the associated shifts in weather systems. In: Book of Proceedings from Greenhouse 2009 Conference. CSIRO publishing. in press.

Hope, P. and B. Timbal and R. Fawcett, 2009: Associations between rainfall variability in the southwest and southeast of Australia and their evolution through time. International Journal of Climatology

Timbal, B. and P. Hope, 2008: Observed Early Winter Mean Sea level Pressure Changes over Southern Australia: a comparison of existing datasets. CAWCR Research Letters Issue, 1, 1-7

Bates, B., P. Hope, B. Ryan, I. Smith and S. Charles, 2008: Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. Climatic Change, DOI 10.1007/s10584-007-9390-9

Rojas, M., P. Moreno, M. Kageyama, M. Crucifix, C. Hewitt, A. Abe-Ouchi, R. Ohgaito, E.C. Brady, P. Hope, 2008: The southern westerlies during the Last Glacial Maximum in PMIP2 simulations. Climate Dynamics

Other Related publications

Hope, P. Report for: McIntosh, P, 2008, Australia's Regional Climate Drivers, report to Managing Climate Variability; My contribution: Comparison of manual analysis with statistical techniques

IOCI-Related Presentations

Hope, P. and C.J. Ganter, 2009: *Historical, recent and projected rainfall trends in Western Australia* (invited), Greenhouse 2009 Conference on Climate Change and Resources, 23-26 March, Perth, Western Australia.

Hope, P., B. Timbal, M. Wheeler and R. Fawcett, 2009: *A strengthening link between rainfall variability in the east and west of southern Australia*. 9th International Conference on Southern Hemisphere Meteorology and Oceanography, 9 to 13 February 2009, Melbourne, Australia

Hope, P., I. Simmonds, M. Pook, K. Keay, J. Risbey and P. McIntosh, 2009: *A comparison of frontal number using a range of identification methods - A case study in south Western Australia* (poster) 9th International Conference on Southern Hemisphere Meteorology and Oceanography, 9 to 13 February 2009, Melbourne, Australia

Ganter, C. and P. Hope: *Changes in intensity of south west Western Australian rainfall* (poster) 9th International Conference on Southern Hemisphere Meteorology and Oceanography, 9 to 13 February 2009, Melbourne, Australia

MILESTONE 1.2.1: NOTE ON THE FREQUENCY OF WINTER WEATHER SYSTEMS IMPACTING THE SOUTH-WEST IN THE LAST FEW YEARS

Background

Summary and Key Research Findings

Annual average rainfall declined in south-west Western Australia in the late 1960s and has not recovered since. A further shift to lower rainfall was identified at approximately the year 2000. The early decline was associated with a decrease in the number of days on which a winter deep low pressure system influenced the region. The recent decline was not associated with a continuing decrease in the number of deep low pressure systems, but rather had a strong contribution from an increase in the number of days when a high pressure system influences the region.

Recent years have also seen extremely high values of winter mean sea-level pressure over SWWA. Both the increased pressures and increased daily occurrence of high pressure systems are as projected for the end of this century by climate models forced with increasing levels of atmospheric greenhouse gases. The magnitudes of the changes expressed by most models suggest that the recent high values might be expected to continue and possibly amplify.

Introduction

During IOCI stage 2, the synoptic patterns that describe the continuum of weather influencing south-west WA (SWWA) in June and July were identified with a self-organising map (SOM). There were 20 different types identified, ranging from deep lows south of SWWA to extensive highs across the continent (Hope et al., 2006). Figure 1 shows the 20 types, and the SWWA rainfall anomaly associated with each..

SWWA rainfall has declined in the last decade (Hope et al., 2009), resulting in a likely downward breakpoint in the timeseries of May to July rainfall averaged over the 'IOCI triangle' (south-west of a line from 30°S, 115°E to 35°S, 120°E, see Figure

4a in milestone report 1.2.2). This downturn in SWWA rainfall continues on from the downward shift observed in the late 1960s, see Figure 2.

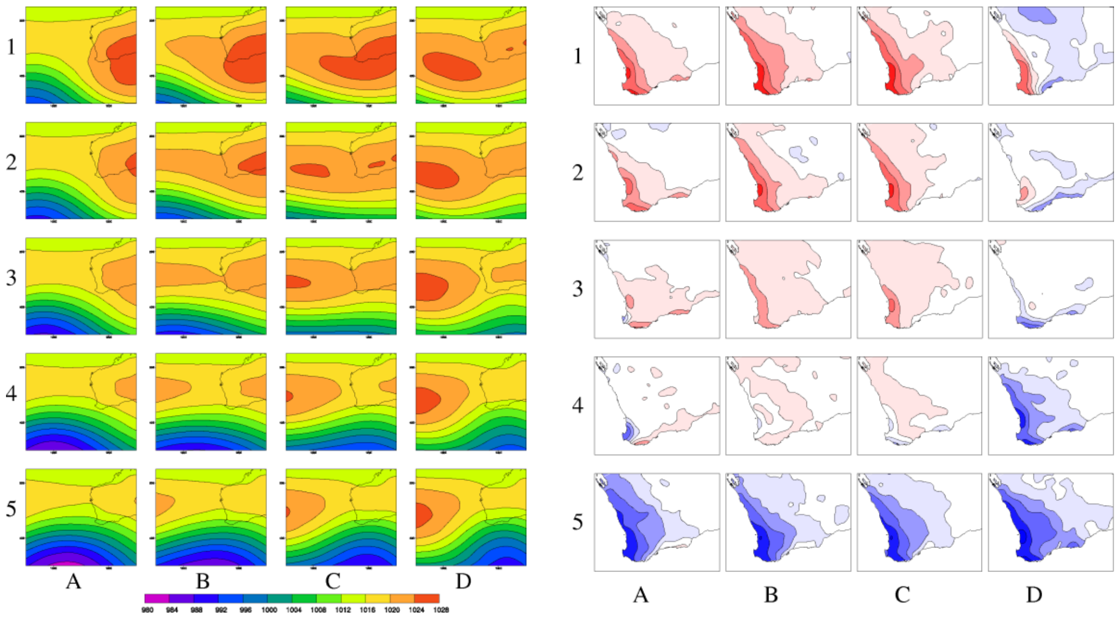


Figure 1.2.1 On the left is the 4 by 5 SOM built using 1948 to 2003 NCEP/NCAR reanalyses MSLP showing the continuum of June and July weather systems that impact SWWA. The reds indicate high pressure and the blues lower pressure. References to individual synoptic types in the text are to, for example, A5, which is the bottom left type. Contour interval is 4 hPa
On the right is the NCC 0.25x0.25 degree gridded rainfall anomalies associated with each type in the 4 by 5 SOM. Red shading indicates conditions drier than the 1958–2003 mean and blue wetter than the mean. The contour interval is variable: -8, -4, -2, -1, -0.3, 0.3, 1, 2, 4, 8 mm/day.
From:Hope et al., 2006.

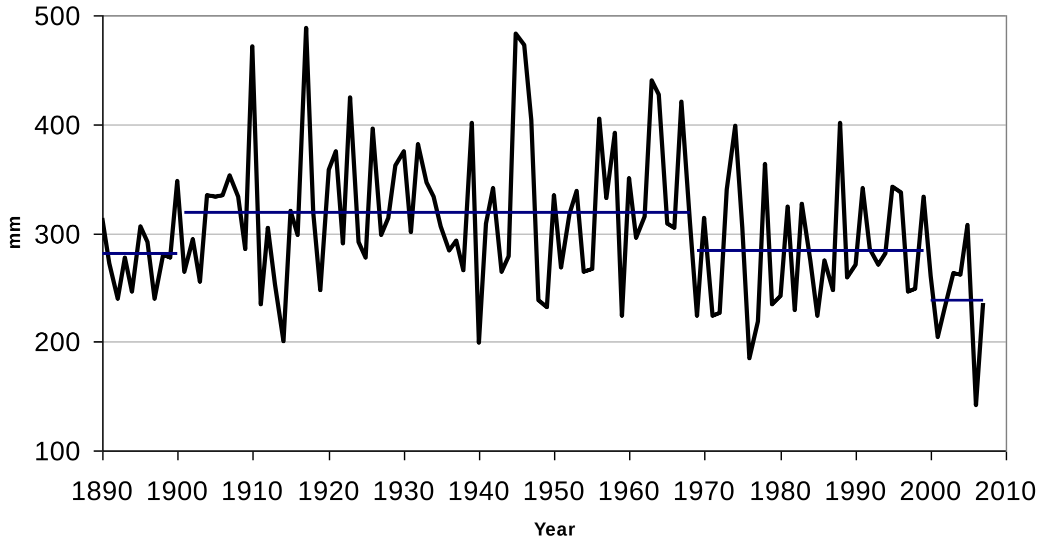


Figure 1.2.2 . Time series of the monthly May to July total gridded rainfall data averaged over the 'IOCI triangle' (south-west of a line from 30ºS, 115ºE to 35ºS, 120ºE). Breakpoints in this series were found at around 1900 (up), 1968/1969 (down) and 1999/2000 (down). (from Hope et al., 2009)

Hope et al. (2006) compared the range of synoptic types influencing SWWA across two epochs, before and after 1975, and found a strong decline in the number of days on which synoptic types typified by a large low-pressure system occurred. There was also an increase in the number of days on which synoptic types typified by extensive high pressure over the region occurred, but this was of less importance.

The aim of this section of Project 1.2 is to determine whether the synoptic types identified by Hope et al. (2006) have altered in their daily occurrence in recent years, and suggest what this might mean for the current and future influences on SWWA rainfall.

Technical Details

Data and Method

Daily maps of June and July MSLP from NCEP/NCAR reanalyses in the years since 2003 were assigned to their most closely matching synoptic type from Hope et al. (2006). Thus the timeseries for each type was extended through to 2008.

Further analysis of the long-term trends in MSLP was conducted using a global MSLP dataset (HadSLP2) from 1890 to 2008 on a 5º latitude by 5º longitude grid (Allan and Ansell, 2006). The MSLP was averaged over the box: 27.5ºS to 37.5ºS and 112.5ºE to 122.5ºE (see Figure 4a in milestone report 1.2.2). Timbal and Hope (2008) compare HadSLP2 with reanalyses for the period 1958-2002 and, although HadSLP2 has lower inter-annual variability, it is believed to be of high enough quality to use for our purposes.

Monthly MSLP data from climate model simulations associated with the fourth assessment of the Intergovernmental Panel on Climate Change (IPCC, 2007) collected by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) in the USA were also used as part of the further analysis. The future simulations were forced following the A2 emissions scenario, which is a scenario following a path with higher emissions than many of the scenarios (Nakicenovic et al., 2000), but which currently falls below the observed levels of atmospheric carbon dioxide.

Results

The daily frequency of occurrence of each synoptic type is shown in Figure 3. The synoptic types associated with extensive wet conditions across the south-west are shown along the bottom of the figure, these all display a deep trough to the south-west of Australia, with low pressures extending over the continent. The driest types are shown along the top of 3, and generally have extensive high pressure across the region, associated with the continental high. Very wet years such as 1964 show a strong representation from a synoptic type associated with extensive wet conditions across the south-west (e.g. A5).

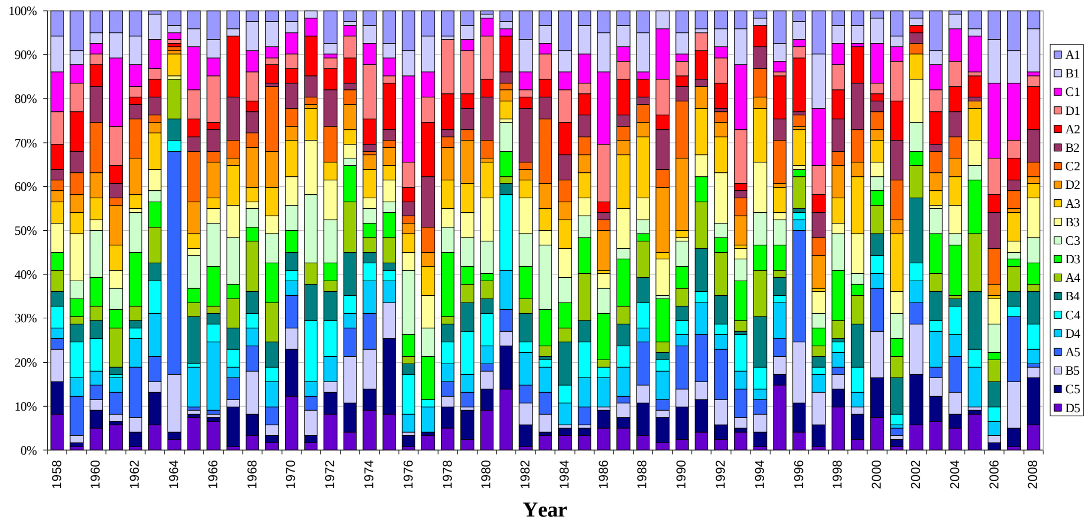


Figure 1.2.3 Time series of each synoptic type from the June and July self-organising map described in Hope et al. (2006). Types associated with extensive wet conditions are shown along the bottom of the plot, while types associated with dry conditions are shown along the top.

The percentage change over the period since 2000 (average of 2000–2008 minus the average of 1958–1999 divided by the average of 1958–1999) in the number of synoptic types associated with wet conditions (D4,A5,B5,C5,D5) was minimal (a reduction of 0.8%); however, the increase in synoptic types associated with a high over the region and extensive dry conditions (A1,B1,C1,B2,C2) was significant at 32%. This indicates that the recent changes have more to do with the persistence of high pressure systems over the region, and less to do with a further decrease in the number of deep low pressure systems. High pressure systems influence a wider region than low pressure systems and thus the recent rainfall declines might have been expected to have a greater spatial extent than the decline in the late 1960s, given the differing shifts in synoptic systems between the two periods. The recent rainfall declines have indeed had a wider spatial extent than those in the late 1960s (Hope and Ganter, 2010 and milestone 1.2.2).

Further results

The results show a clear shift in the daily occurrence of particular synoptic systems. However, this may be due to a background shift in MSLP. Time was spent to explore this question further. The May to July 1890–1968 average MSLP for the SWWA box from HadSLP2 was 1017.8 hPa, while the average from 1969–1999 was 1018.3 hPa, an increase of 0.5 hPa. That increase has persisted through the rainfall decline since 2000. 2006 was a record-breaking year, with very low rainfall totals and MSLP values well above normal across southern Australia. Figure 4 shows the time series of May to July MSLP over the south-west, clearly showing that recent years were all near or above average.

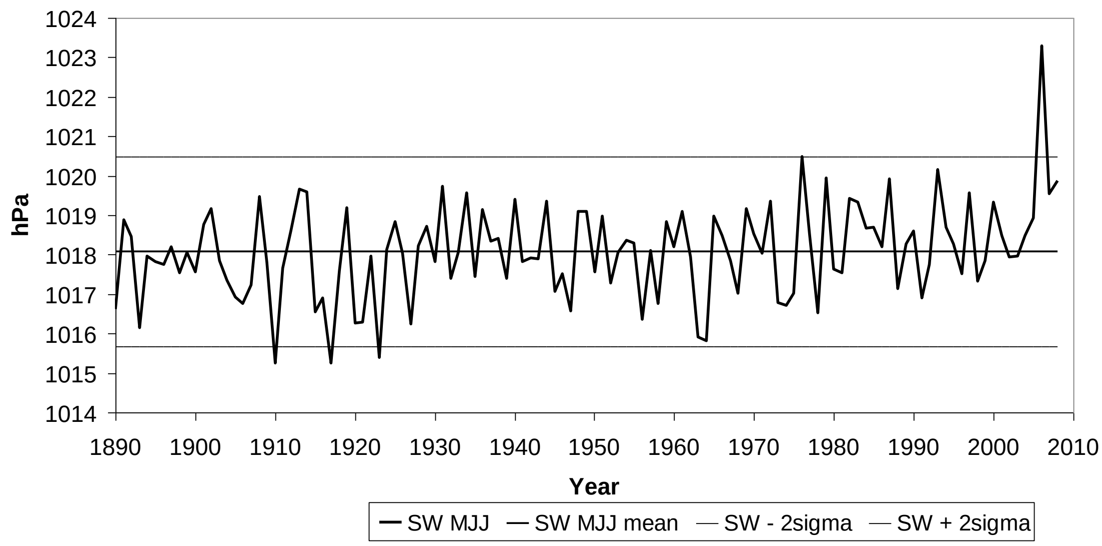


Figure 1.2.4 Mean May to July mean sea-level pressure (HadSLP2r) averaged over a square encompassing south west WA. Also shown are the mean over the 1890 to 2008 period and +/- 2 standard deviations either side of the mean.

The designation of each day's MSLP pattern to a particular synoptic type in the SOM from Hope et al. (2006) is dependent on the magnitude of the MSLP as well as the pattern. Thus a background of increasing MSLP might be expected to produce the shifts to fewer low-pressure systems and more high pressure systems described above. To test whether the shift in the daily frequency of particular synoptic types was due to the background pressure increases or an actual shift in the circulation, another method of defining high pressure systems that depends on the local gradients rather than the absolute magnitude (Murray and Simmonds, 1991), was investigated. The trends in the density per unit area of high pressure systems calculated using this method have been produced at the Bureau of Meteorology's National Climate Centre (displayed at: www.bom.gov.au/silo/products/cli_chg/). In all seasons except summer, there is a clear upward trend in the number of systems (e.g. Figure 1.2.5 for the June to August trend from 1970 to 2008). This indicates that there has not only been an upward trend in average MSLP across southern Australia, but the occurrence of high pressure systems has also increased markedly.

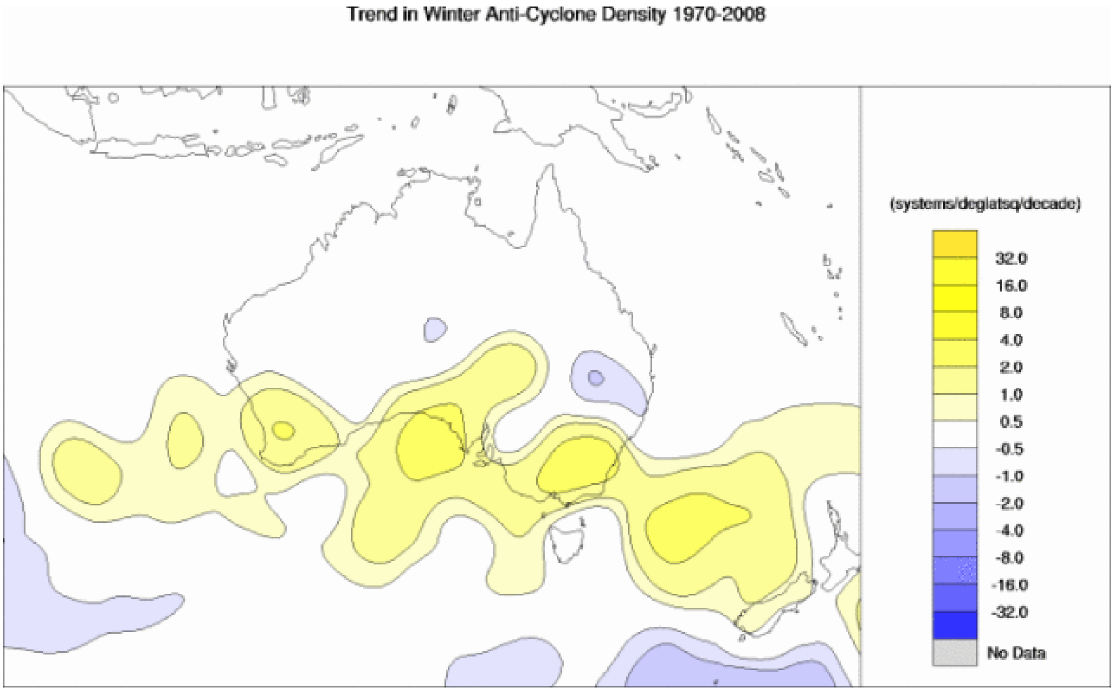


Figure 1.2.5 . Trend in the density of high pressure systems in June to August from 1970 to 2008. From Bureau of Meteorology website: http://www.bom.gov.au/silo/products/cli_chg/

Discussion

The results for this milestone suggest an on-going increase in MSLP across SWWA in winter. In recent years this increase has been driven by a shift to a higher number of days when a high pressure system influences the region. This may be due in part to an expanding continental high (Larsen, 2008), however the pattern of the trends in high pressure systems from the Bureau of Meteorology indicates that it is part of a wider signal. These changes are consistent with the weakening of the meridional thermal gradient and the decrease in the potential for storm development as noted by Frederiksen and Frederiksen (2005)

Climate model projections of MSLP under increasing levels of atmospheric greenhouse gases show strong increase in MSLP across the Australian region. (Meehl et al., 2007). The mean climate model response (for 2080–2099 compared to 1980–1999, and a mid-range forcing) is of the order of a 1.5 hPa increase in the south-west. Individual climate model simulations investigated for this milestone show MSLP increases of up to 4 hPa, while others have a more bland response. Thus the exceedingly high pressures in 2006 might be more common-place in the future.

The recent changes in the daily frequency of occurrence of synoptic systems assessed in this part of Project 1.2 can be compared with the projected daily frequency for 2081-2100 under the A2 scenario from five climate models assessed by Hope (2006). Type A1, associated with dry conditions across SWWA, is projected to decrease in its daily occurrence, possibly due to the deep low pressure region to the west of the continent. However, types B1, C1, D1, C2 and D2, which all show extensive high pressure across all the longitudes in the selected region for the SOM show strong increases in daily occurrence in four of the five climate models. There are increases of greater than 70% compared to 1961-2000 counts for type C1 shown by two of the models. These results are in agreement with the trends in the occurrence of high pressure systems since 1970, which show increases at southern Australian latitudes right around the globe. Thus the recent observed increase in the daily occurrence of synoptic types with extensive high pressure across the region might be expected to continue and possibly amplify.

Conclusions

The daily frequency of occurrence of winter weather systems in recent years showed a steady number of deep low pressure systems, and an increase in the number of days when a high pressure system influences the region. This result coincides with the observed declines in May to July SWWA rainfall which could be described as a step drop since 2000.

Recent years have also seen extremely high values of winter MSLP over SWWA. Both the increased pressures and increased daily occurrence of high pressure systems are as projected for the end of this century by climate models forced with increasing levels of atmospheric greenhouse gases. The magnitudes of the changes expressed by most models suggest that the recent high values might be expected to continue and possibly amplify.

References

Allan R and Ansell TJ, (2006) A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850-2004. *Journal of Climate*, **19,** 5816-5842.

Frederiksen CS and Frederiksen JS, 2005: Mid-1970s changes in the Southern Hemisphere winter circulation. *Indian Ocean Climate Initiative Stage 2: Report of Phase 1 Activity*, Ryan B and Hope P, Eds., http://www.ioci.org.au/.

Hope P and Ganter CJ, 2010: Recent and projected rainfall trends in south-west Australia and the associated shifts in weather systems. *In: Book of Proceedings from Greenhouse 2009 Conference*, CSIRO Publishing. *(in press)*.

Hope P, Timbal B, and Fawcett R, (2009) Associations between rainfall variability in the southwest and southeast of Australia and their evolution through time. *International Journal of Climatology*.

Hope PK, (2006) Projected future changes in synoptic systems influencing southwest Western Australia. *Climate Dynamics*, **26,** 765-780.

Hope PK, Drosdowsky W, and Nicholls N, (2006) Shifts in synoptic systems influencing south west Western Australia. *Climate Dynamics*, **26,** 751-764.

IPCC, 2007*Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, and Miller HL, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996pp.

Larsen SH, (2008) Australian winter anticyclonicity, 1850-2006. *Journal of Geophyscial Research*, **113,** D06105.

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, and Zhao Z-C, 2007: Global Climate Projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, and

Miller HL, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Murray RJ and Simmonds I, (1991) A numerical scheme for tracking cyclone centres from digital data. Part I: Development and operation of the scheme. *Aust. Met. Mag.*, **39**.

Nakicenovic N, Alacamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grubler A, Jung TY, Kram T, La REL, Michaelis L, Mori S, Moita T, Pepper W, Pitcher HM, Price L, Raihi K, Roehrl A, Rogner HH, Sankovski A, Schlesinger M, Shukla P, Smith SJ, Swart R, van Rooijen S, Victor N, and Dadi Z, 2000: *Emissions scenarios, A special report on Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Timbal B and Hope P, (2008) Observed early winter mean sea level pressure changes over southern Australia: a comparison of existing datasets. *CAWCR Research Letters*, **1,** 1-7.

MILESTONE 1.2.2: REPORT ON THE RAINFALL VARIABILITY AND TRENDS IN ALL SEASONS. HAS THERE BEEN A SHIFT IN RAINFALL INTENSITY OVER THE LAST 40 YEARS?

Background

This milestone expands beyond the wintertime changes in south-west Western Australian (SWWA) rainfall explored in IOCI Stages 1 and 2, and takes a broader view, by investigating rainfall variability on a monthly and seasonal scale.

Both gridded and station level rainfall data were used. High quality station data were re-assessed and unfortunately a number of station records needed to be discarded or shortened due to reductions in observation quality or closure.

The large decline in early winter (May to July) SWWA rainfall in the late 1960s has persisted and expanded spatially. Both trends and percentage change were analysed to explore this. Trends reveal that regions where rainfall did not decline in the late 1960s are now seeing a decline in early winter, whilst the percentage change analysis revealed that since 2000 *all* regions across SWWA are experiencing increasingly dry conditions. The interannual variability in the far south-west continues to decline. Trends in 95^{th} percentile rainfall were generally weak, except along the south coast since 1970 and at Manjimup since 1950. The evidence at Manjimup suggests that the decline in early winter rainfall in the late 1960s was driven strongly by a decrease in the occurrence of wet events – most likely associated with deep low pressure systems. However, such events have not contributed to the strong downward trend in total rainfall since early 1970. This supports the findings in Milestone 1.2.1: that recent rainfall declines were not associated with a further decrease in the daily occurrence of deep low pressure systems, and therefore no further decrease in associated extreme rainfall.

In the summer half year there were positive trends in totals and extremes from both 1950 and 1970 inland (Bulong) and along the south coast (Peppermint Grove). The trends in 95^{th} percentile rainfall since 1970 were strong compared to the totals, suggesting that extreme events have had a growing impact on the increases in totals at these stations. Negative trends were evident in the far south-west.

Analysis of 'standard' seasons was found to potentially mask important information, as found by the analysis of the standard spring (September to November) and late winter (August to October) trends. There were only weak trends from 1950, but some stronger trends from 1970 in late winter: increases at Manjimup and Nyerilup and decreases at Peppermint Grove. The map of spring trends showed decreases everywhere. Examining the decadal variability by month in the far south-west revealed that rainfall in August and September had been increasing, but decreasing in October and November. Global climate model results suggest that spring rainfall will decline in the future, however, these sub-seasonal variations in trend direction have encouraged a more detailed analysis of the model results, which is on-going.

Introduction

During the IOCI Stages 1 and 2 the rainfall decrease in the far south-west was investigated. It was found that the decline consisted of a step change in the late 1960s and a dearth of years with 'very high' rainfall totals in the later period (Hope and Foster, 2005: IOCI, 1999: IOCI, 2002). The declines were particularly in May, June and July, and much of the research in the early stages of the IOCI focussed on the winter period.

The signature of the change meant that trend analysis could limit the understanding of what was happening, and that the traditional winter season of June, July and August would not indicate the severity of the decline. In Stage 3 all months will be considered, as well as the decadal variability. Trend analysis will be used to assess whether there has been a shift in rainfall totals or extremes since the decline in the late 1960s for key seasons. A high quality rainfall dataset was used in IOCI 1 and 2, which will be re-assessed (tying in with 1.4), and the best quality data available will be used.

Observed regional rainfall totals in late winter and spring did not decline in the late 1960s, however some climate models indicate that a decline will occur. An analysis of trends over the last 40 years (since 1970) will reveal whether the late winter season is now showing some sign of a trend. Summer rainfall totals also showed minimal signal in their trends since the 1950s. In this milestone we will explore whether there has been a shift in extreme summer rainfall, despite the minor trends in the totals.

The aim of this section of Project 1.2 is to describe the rainfall variability and trends, not only in the far south-west corner in winter, but in all seasons and across the wider south-west of WA. Any shifts in rainfall intensity will also be discussed.

Technical Details

Data

The monthly rainfall dataset is the Australian Bureau of Meteorology's National Climate Centre (NCC) gridded monthly rainfall analyses from 1890 to 2007. The data is on a 0.25º by 0.25º latitude-longitude grid, based on all available station data of reasonable quality available at any one time Jones and Weymouth, 1997. Temporal variations in the network can therefore have an impact on the trends. Monthly time series of area-averaged SWWA rainfall were created. The May to July average time-series will be termed R_{MJJ}. Hope et al. (2009) provide some of the background as to the choice of the 'IOCI triangle' region.

Monthly and daily station rainfall data were extracted from the Bureau of Meteorology's archive. The shortlist of stations selected for this study were chosen initially from the high quality daily rainfall dataset, as first mentioned by Lavery et al. (1992), then updated by Haylock and Nicholls (2000). In some regions the daily set provided limited spatial coverage, thus the quality of the daily data for stations on the high quality monthly rainfall dataset (Lavery et al., 1997) was also assessed. After the quality checking described below, the stations selected from this monthly set were: Doongin Peak, Yuna and Bulong. To further extend the spatial coverage, some stations with shorter, though still high quality, records were considered (Telina Downs and Mt Madden were selected). A number of stations had to be discarded due to poor records or closure in the last decade: Moora (8091), Boyanup (9503), Grassmere (9551), Pardelup (9591), Arthur River (10505) and Pinnacles (12067).

The quality of the stations on the short-list was then re-assessed. This checking was primarily for "untagged" accumulations of daily rainfall totals (Viney and Bates, 2004). Untagged accumulations are a problem when using daily data, as they bias statistical analysis. They produce larger rainfall totals, and less days of rain. Further checking for untagged accumulations was done by Robert Smalley (pers. comm., 2007). If untagged accumulations were found, the data were posted as missing. All selected stations were free of untagged accumulations except during 1987 at Peppermint Grove (9594). An analysis of the number of rain-days also highlighted periods where untagged accumulations were highly likely.

A rain-day is any day with rainfall greater than 0.3 mm. The plots of Manjimup May to October rain-days compared to totals shows a sharp increase in the number of rain-days after 1936, when it was upgraded to a synoptic station, but the totals were high in the years before this time. This suggests that there were untagged accumulations every year prior to 1936, and these years were discarded from the analysis of daily rainfall. There was a similar story at Nyerilup, and also at Wilgarrup. Unfortunately, the concerns at Wilgarrup are at the end of the record (see Figure 1), thus it was removed from the analysis of daily data, and Manjimup was used instead.

There are concerns with the quality of Manjimup's record, due to a site change in 1989/1990, and thus it is not on the high-quality list, however, it is one of the only stations with a reliable, lengthy record in the very wet far south-west, without being right on the coast. There may be further concerns with the consistency of Manjimup's record before and after the year 2000, when a tipping bucket rain gauge (TBRG) was installed, and the manually read 203mm rain gauge removed. The TBRG's tend to over-read heavier rainfall, and as Manjimup is an area of heavy rainfall, the decline seen in our results could potentially be underestimated slightly (Srikanthan et al., 2002).

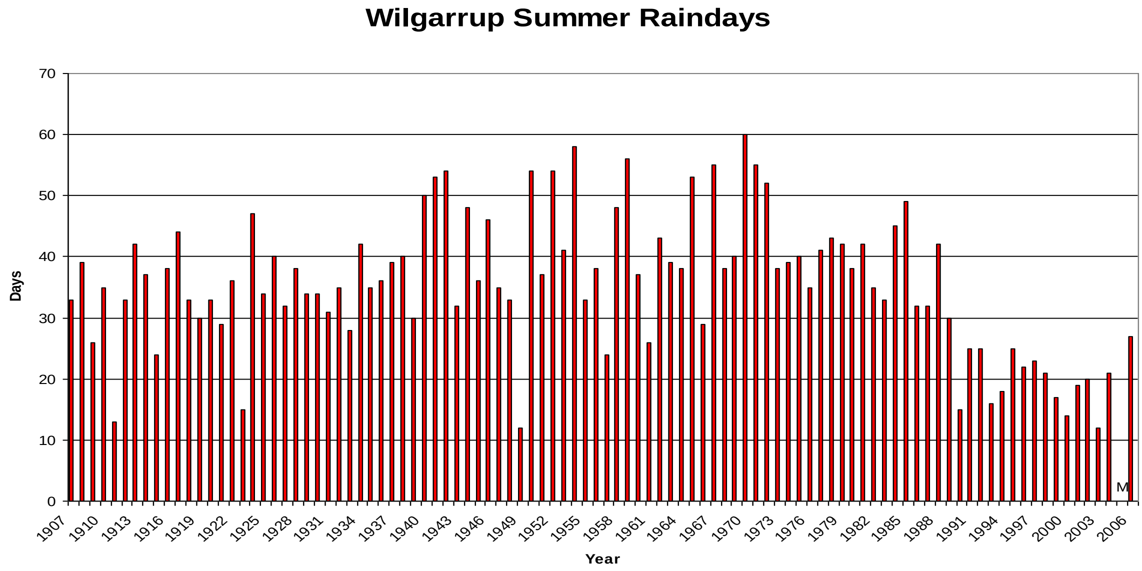


Figure 1.2.6 The number of days with rainfall greater than 0.3 mm at Wilgarrup for November to April. A new observer started at the same time as the number of rain-days dropped sharply.

The final list of stations selected for this study are listed in Table 1.2.1.

Table 1.2.1 The final list of stations deemed to be of high quality, reasonable duration and that provide good spatial coverage for use in this study. Those stations not in italics were used for the extreme rainfall study.
*** Date from which there was consistent data. The dates in brackets indicate a shortening of the record for use with daily data due to accumulations found in the rain-day analysis.**

Name	**Station Number**	**Coords**	**Date Began***
Manarra	8079	29.07S, 115.63E	1907
Perangery	8106	29.37S, 116.41E	Sep 1910
Yuna	8147	28.33S, 114.96E	Aug 1909
Cape Naturaliste	9519	33.54S, 115.02E	1907
Manjimup	9573	34.25S, 116.15E	1916 (1936)
Peppermint Grove	9594	34.44S, 119.36E	1907
Wilgarrup	9619	34.15S, 116.20E	1907 (last yr 1989)
Telina Downs	9739	33.68S, 122.33E	Dec 1961
Doongin Peak	10041	31.62S, 117.44E	Feb 1907
Nyerilup	10541	33.86S, 118.82E	1911 (1916)
Mount Madden	10611	33.28S, 119.78E	Feb 1932
Bulong	12013	30.75S, 121.75E	1907

Results

Totals

The calculation of trends relies on the temporal consistency of the underlying data. A sense of the spatial pattern of rainfall trends across the south west of Australia can thus be produced in a number of ways. One way is to take the gridded products from the National Climate Centre at the Australian Bureau of Meteorology and produce trends at each grid point. This method makes use of all available data at any given time (of appropriate quality), however, it can introduce errors from temporal inconsistencies, such as those resulting from observing stations closing. The mean trends were produced in this way by Alexander et al. 2006. Another method is to calculate the trends at each observing station and then spatially interpolate the results. These generally provide less information spatially due to the reduced number of stations used. The trend maps on the Bureau of Meteorology website were created in this way. Another method is to provide trend information at each station location and present this on a map. Each method has strengths and weaknesses, but the focus in this milestone will be on what the results tell us.

The strong decline in winter rainfall in SWWA is clearly seen in the top right image of Figure 2. There were also strong declines in autumn (top left) and minimal change in spring and summer (bottom left and right, respectively). However, trends calculated for winter rainfall in the far south-west that span the statistically robust step-change in the late 1960s will always show a decline due to the intensity of that decline. To investigate whether the decline in the late 1960s has persisted, or whether other seasons are showing shifts in their rainfall, the trends starting in 1970 are also shown (Figure 3). Trends in summer continue to be weak, and the declines in winter and autumn appear to continue, particularly in the far south-west. The trends for spring suggest that SWWA may now be becoming dryer in that season also.

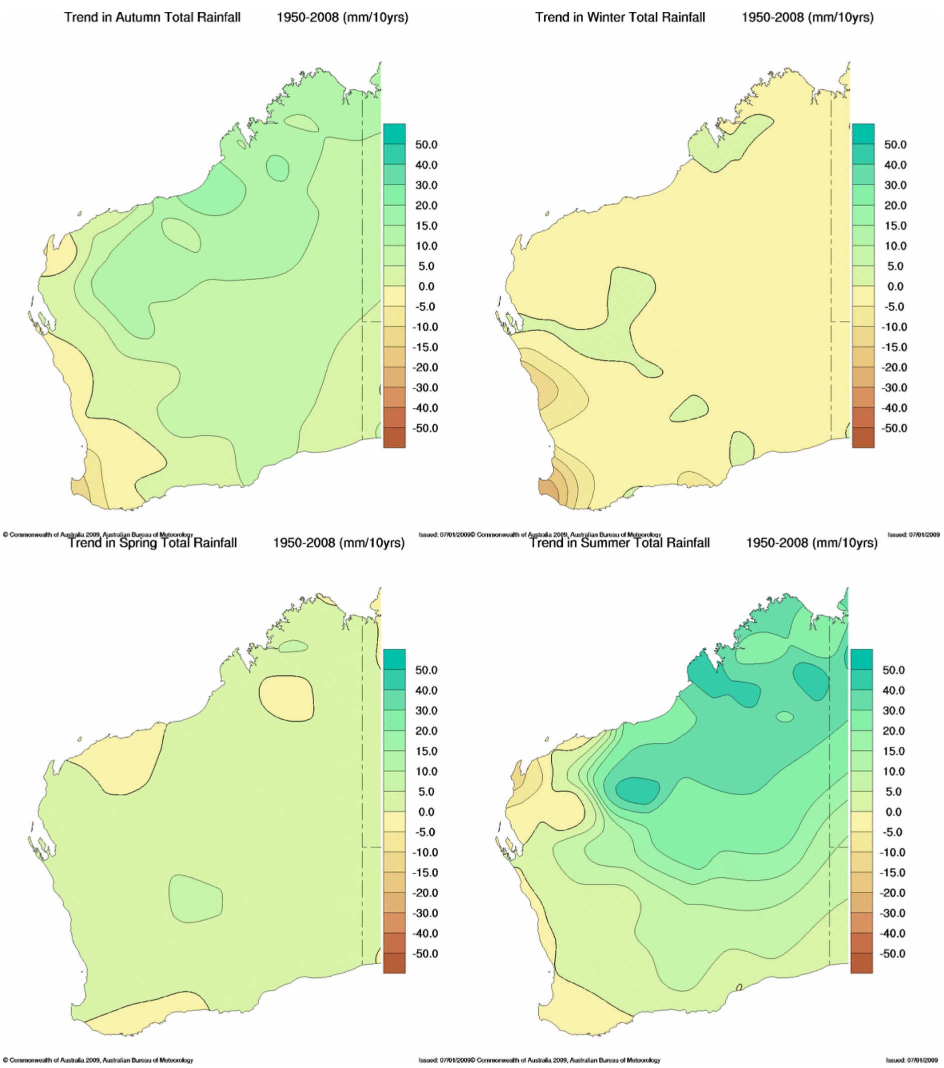


Figure 1.2.7 Trends in rainfall totals for each season from 1950 to 2008 (mm/10 yrs). These maps are interpolated from trends calculated at stations. http://www.bom.gov.au/cgi-bin/climate/change/trendmaps.cgi

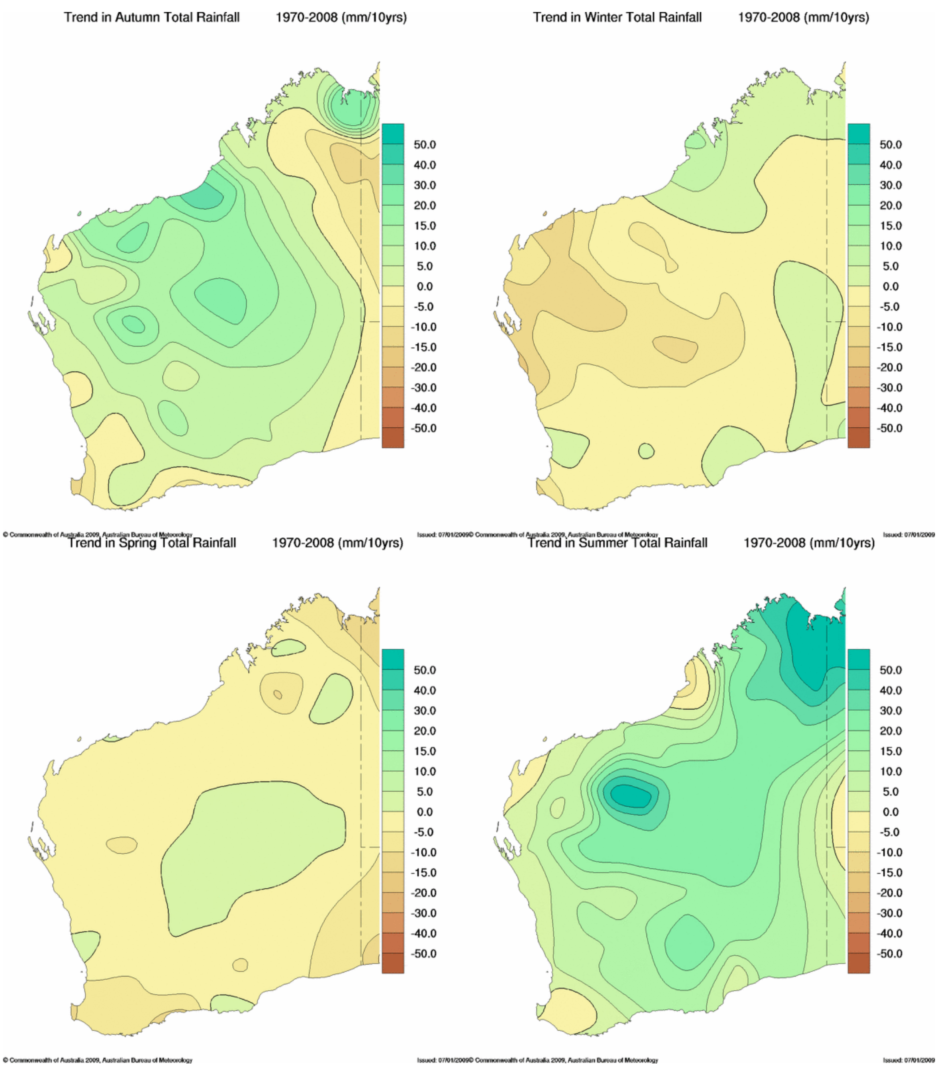


Figure 1.2.8 As Figure 1.2.7, but trends from 1970 to 2008

The rainfall decline in the late 1960s was found to be particularly in May, June and July (Hope and Foster, 2005: IOCI, 1999: IOCI, 2002). A statistical break-point was found by Hope et al. (2009) in the R_{MJJ} across 1968/69 and 1999/2000. Thus, rather than using a trend analysis to describe the changes in SWWA, the percentage change in the means around these years was calculated (Figure 1.2.9), which clearly shows the continuing declines in the far south-west, and the extraordinary spatial expansion of the signal in these key months in recent years.

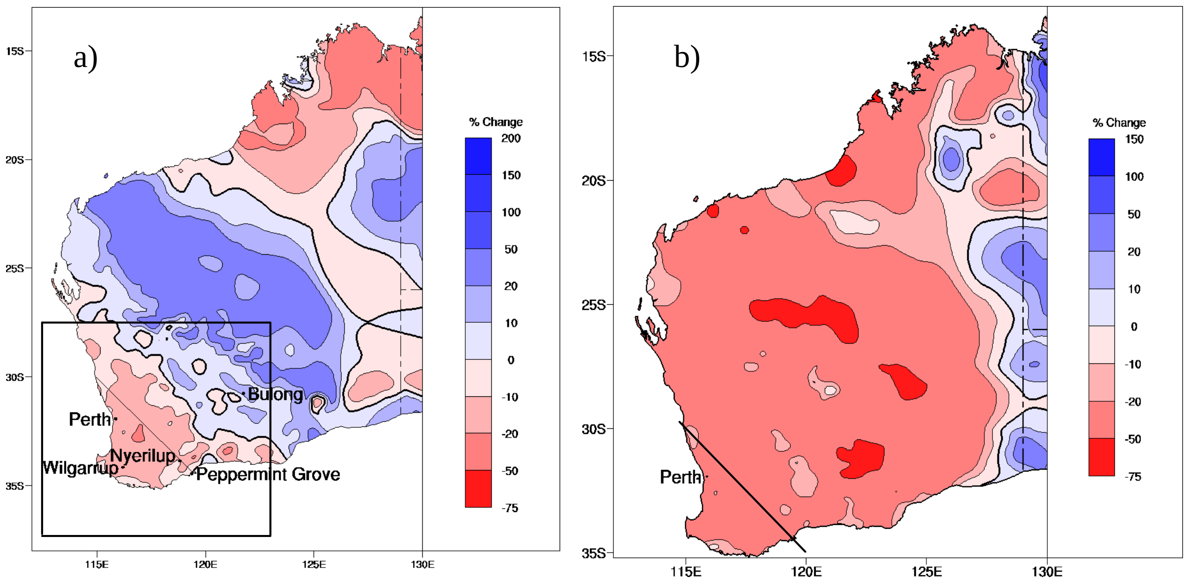


Figure 1.2.9 a) The percentage change in average 1969-1999 May to July gridded rainfall from the 1910-1968 mean. Also shown is the 'IOCI' triangle that delimits the region considered for averaging south west rainfall, the location of some of the high-quality rainfall stations referred to in the text and the square over which HadSLP2r MSLP data were averaged for Milestone report 1.2.1. b) As a, but the 2000-2008 average compared to the 1910-1968 mean.

As discussed above, discontinuities in the station data that have been used to create the gridded rainfall to produce Figure 1.2.9 may artificially influence the patterns described. To avert any concerns in this regard, the percentage change at stations representative of particular climate regions across SWWA are shown in Table 2. It is very clear that the dominant trend right across the south-west is to lower rainfalls in May, June and July. Areas that showed no decline in the late 1960s have seen large reductions in their rainfall totals in the last decade.

Table 1.2. 2 Percentage change in average May to July rainfall between the epoch stated and the 1910-1968 mean for stations from a number of regions across SWWA

Region (station)	**1969-1999**	**2000-2007 (2000-2009)**
Far south-west (Wilgarrup)	-25%	-44% (-39%)
Wheat Belt (Nyerilup)	-14%	-35% (-33%)
South coast (Peppermint Grove)	+7%	-15% (-13%)
Inland (Bulong)	+22%	-42% (-35%)

The methods to statistically find a break in a time-series may be questioned (Richard Chandler, 2009), and thus a simple assessment of the means and variability in the R_{MJJ} timeseries is shown in Table 3. These numbers illustrate that there have been strong shifts in the behaviour of the rainfall across SWWA in May to July. It was stated during IOCI, Stage 2, that an important signature of the rainfalls since the decline in the late 1960s is the dearth of years with very high totals, which can clearly be seen in Figure 3 of IOCI Milestone Report 1.2.1 (this volume). Table 3 shows that there was a corresponding reduction in inter-annual variability. To illustrate how the shifts in variability have manifested through time, the decadal variability was explored by plotting the standard deviation of 11 year periods (Figure 1.2.10). There was high inter-annual variability during the 1950s, and this reduced markedly after the declines in rainfall totals in the late 1960s. The inter-annual variability has continued to decline.

Table 1.2.3 Average May to July total gridded rainfall for the IOCI triangle (R_{MJJ}) for relevant epochs; and the standard deviation within that epoch

Epoch	Average May-July rainfall (mm)	Standard Deviation (mm)
1890-1900	281	33
1901-1968	319	67
1969-1999	284	56
2000-2007*	238	49

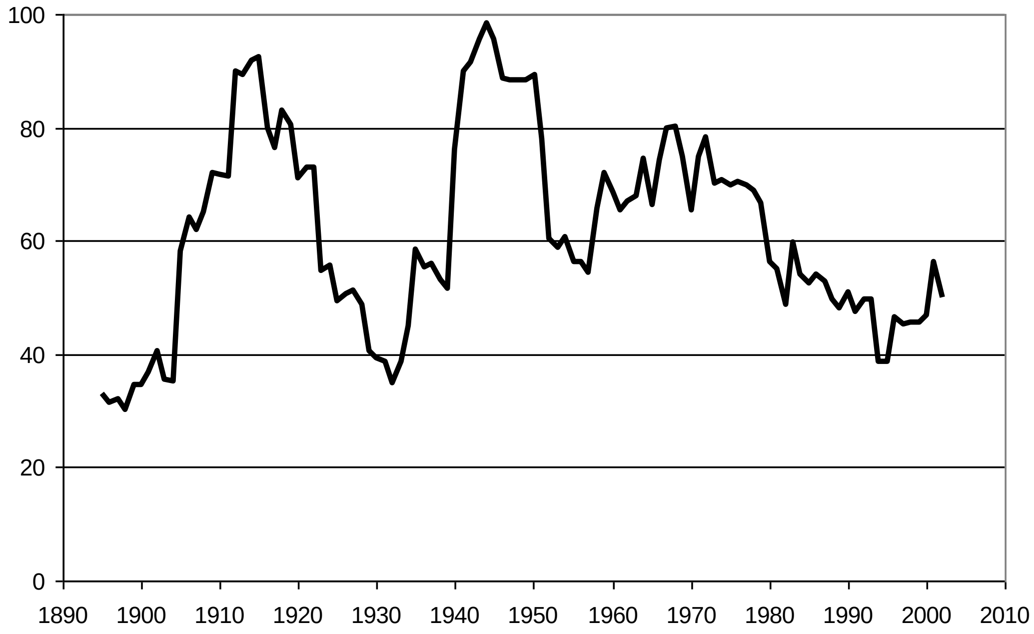


Figure 1.2.10 Standard Deviation of R_{MJJ}, for 11 year periods, plotted at the mid-year.

As stated above, due to the dramatic decline in rainfall totals in the late 1960s in winter in the far south-west, any trend analysis that starts before the decline and ends after it will always show a downward trend. Thus, to describe the long-term variability in rainfall across the south-west in a more informative manner, decadal averages were plotted, acting as a low-pass filter. Generally studies of rainfall variability in the south-west have examined linear trends or the difference between two epochs. Gallant et al. (2007) is an exception, presenting their results as a ten year running mean. However, they did not retain the information about spatial variability as they averaged station data to produce single time-series.

Representing rainfall variability and trends at a glance across regions with high spatial heterogeneity in their rainfall signature can be a challenge. This is because to fully represent variability at a site, a first step is to understand the underlying seasonal cycle. To explore the decadal variability and seasonal cycle across the region, decadal averages of the monthly rainfall at each high-quality station selected for this study were plotted together. This forms a timeseries for each month. Utilising the power of a web-based image, we provide an overview of how the seasonal cycle varies across the region, and then allow for more detail to be obtained by clicking on stations of interest (http://www.ioci.org.au).

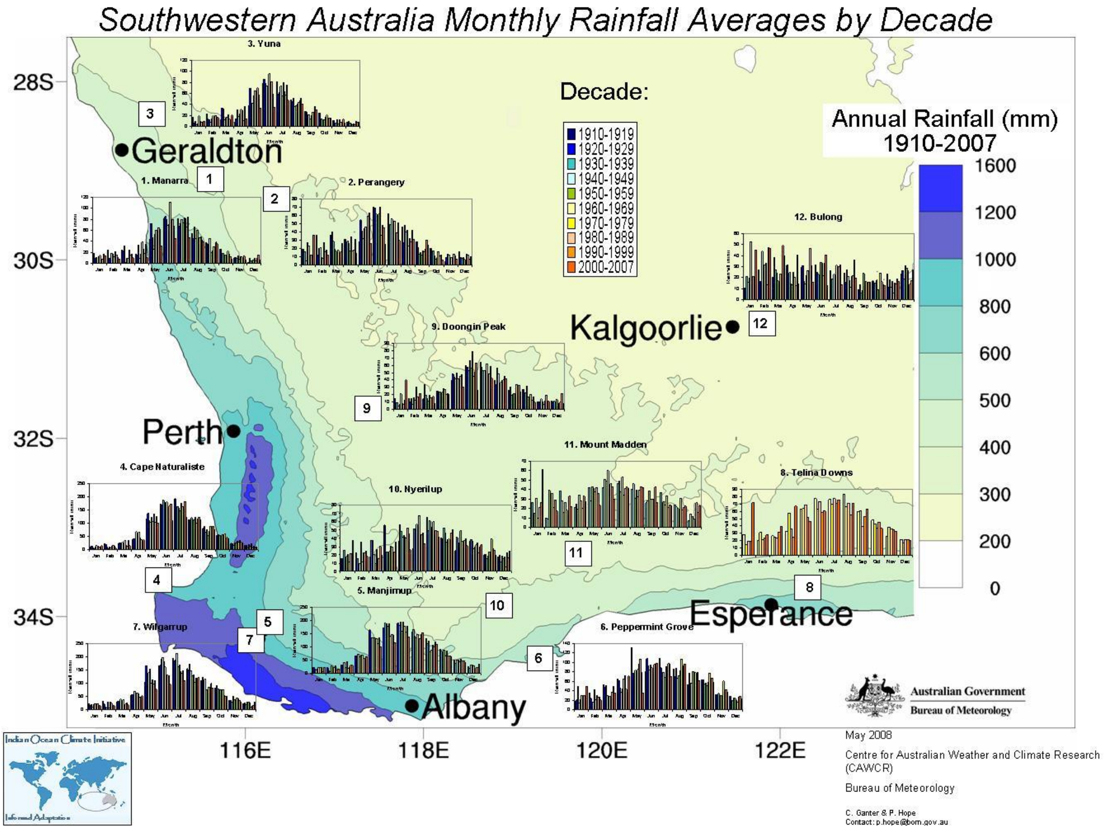
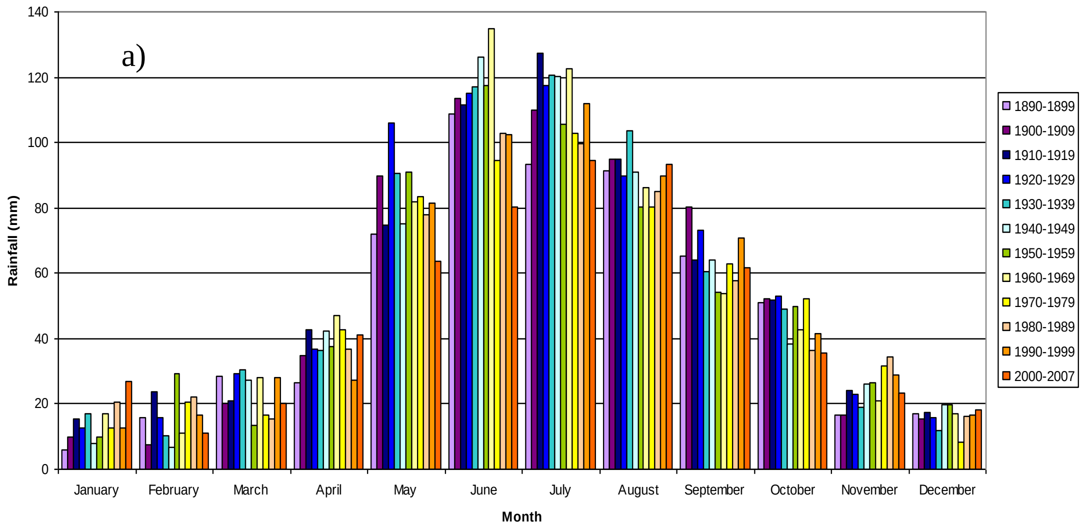


Figure 1.2.11 The poster created to display the seasonal cycle and decadal variability of each month at high-quality stations across Australia's south-west. This has been placed as a 'clickable' image on the IOCI website, so that the plot at each station can be viewed in detail (http://www.ioci.org.au)

Producing simple decadal averages requires a decision to be made about the start and end years, and it is likely that that decision will alter the resulting pattern of the time-series slightly. Figure 1.2.12 shows the plots of the decadal monthly variability for the 'IOCI triangle', with decades starting on years ending in '0' or '7'. Minor differences appear: for example, in May and June, the 2000-2007 average value is by far the driest compared to other decades, whereas the 1997-2006 value is less different from earlier decades, although it is still the lowest. It was decided to use years ending in '0' as the start date in line with the likely break found in the data across 1999/2000 (Hope et al., 2009).



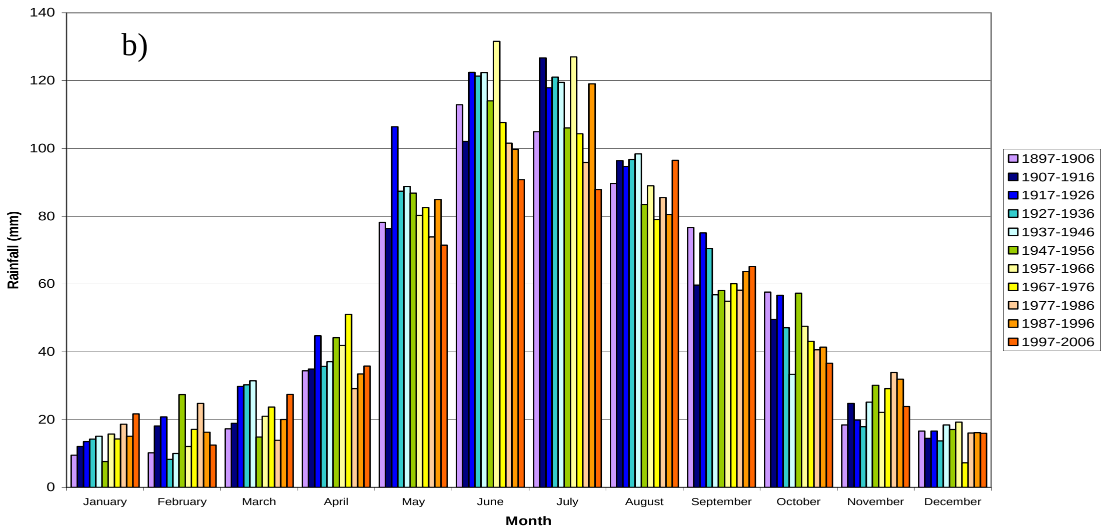


Figure 1.2.12 The decadal variability of each month for the 'IOCI triangle'. Figure a) shows decades starting with years ending in '0', while b) shows decades starting in years ending in '7'. Note that in a) there is an extra decade, and the colouring of the first three decades varies from the first two in b).

The poster shown in Figure 1.2.11 immediately illustrates the winter dominated seasonal cycle across most of SWWA. Further inland the cycle breaks down and the annual totals also drop dramatically. Bulong has a reasonably flat seasonal distribution. Looking in more detail reveals the dramatic decline in May and June rainfall across the region in the last decade. At Peppermint Grove (Figure 1.2.12), which did not experience a decline in the 1960s, the average total for the 2000-2007 period is by far the lowest for May, and very close to the lowest in July. However, June shows no change. June rainfall at Telina Downs is also low in the most recent decade, but not spectacularly so. This suggests that whatever is causing the recent rainfall decline is impacting the south coast in May, but the impact in June that is affecting the rest of the region is not reaching so far south. There is a hint that summer months are showing an increase in rainfall across some of the stations.

Nyerilup appears to delineate the regions of influence between the south coast stations and the rest of SWWA. There seems to be a seasonal difference between the extent of influence. During winter months (May to August) Nyerilup has a similar decadal rainfall pattern to Doongin Peak. Whereas in the summertime months of January, February and March, Nyerilup is very similar to Peppermint Grove.

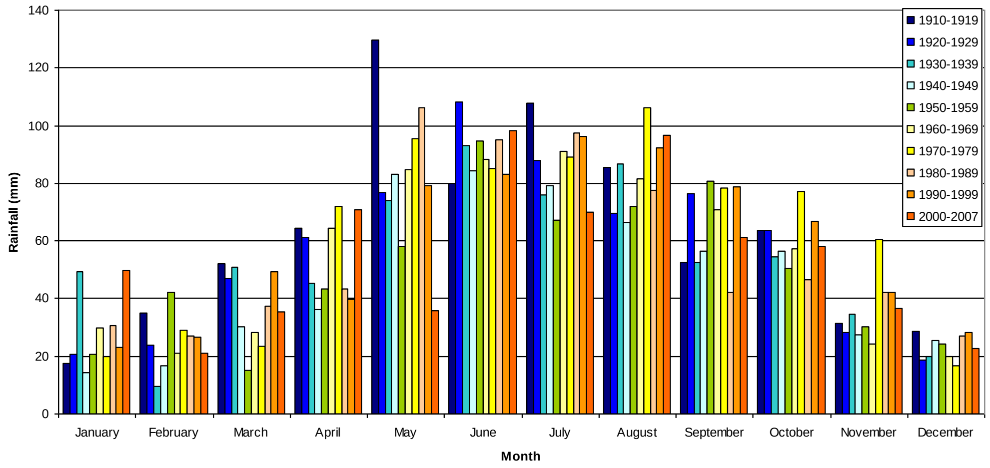


Figure 1.2.13 Decadal variability for each month at Peppermint Grove.

The mean rainfall in the south-west for December to February shows a region of higher rainfall along the south coast compared with the west coast, and a band of higher rainfall extending down from the tropics (Figure 1.2.14). Preliminary work for Milestone 1.2.3 has shown that the band of higher rainfall is particularly weak during the 1961-1990 period, while before and, particularly, after that time the values are much higher. This is reflected in the decadal variability in the summer months for stations situated within this band. The top 20 days with high totals along that band that were investigated for Milestone 1.2.3 were associated with the breakdown of tropical cyclones or lows.

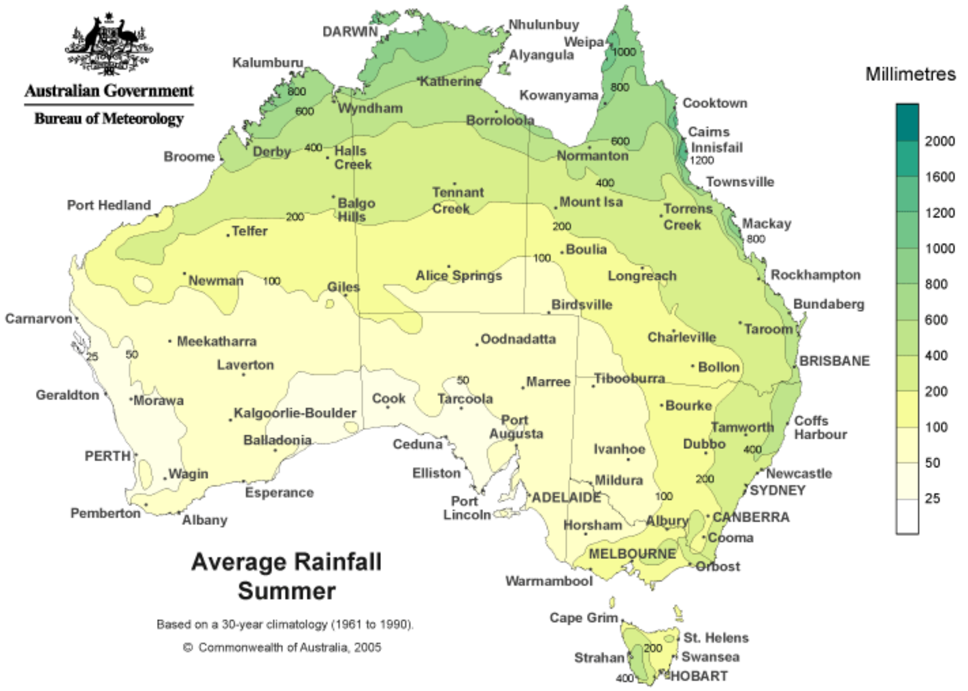
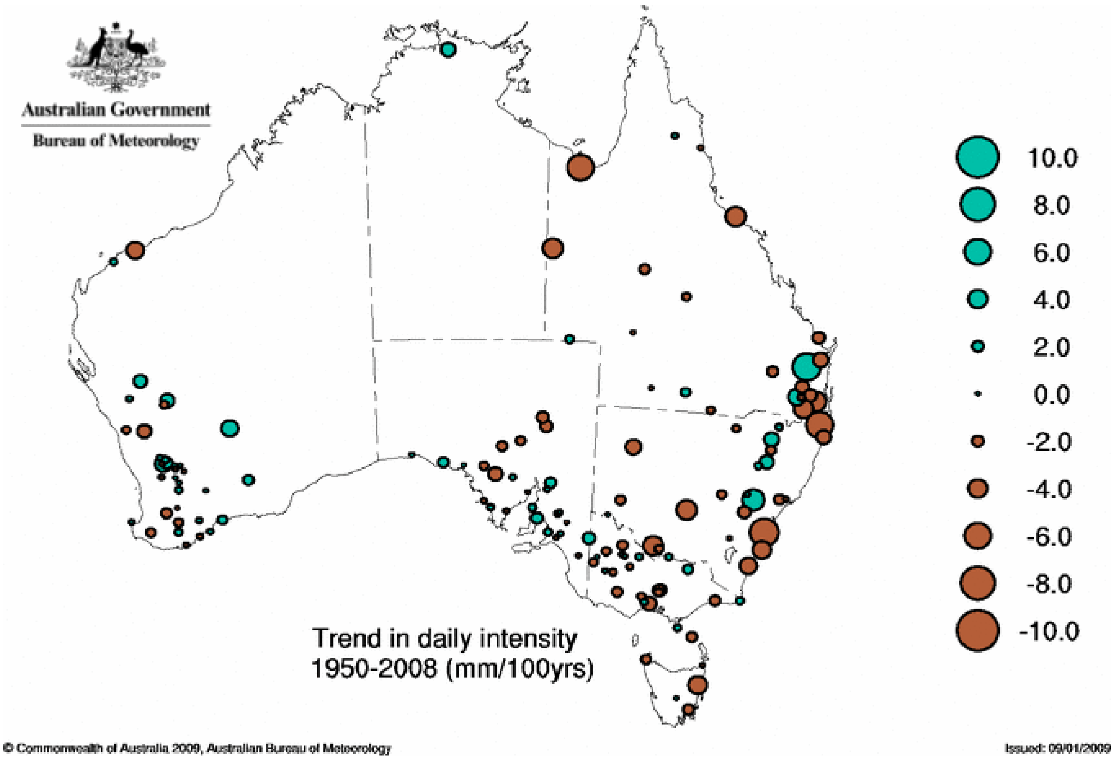


Figure 1.2.14 Mean average December to February rainfall, 1961-1990.

Extremes

Rainfall intensity can refer to a number of different measures. The Bureau of Meteorology describes it as the total annual rainfall divided by the number of rain-days. They present trends on their website:



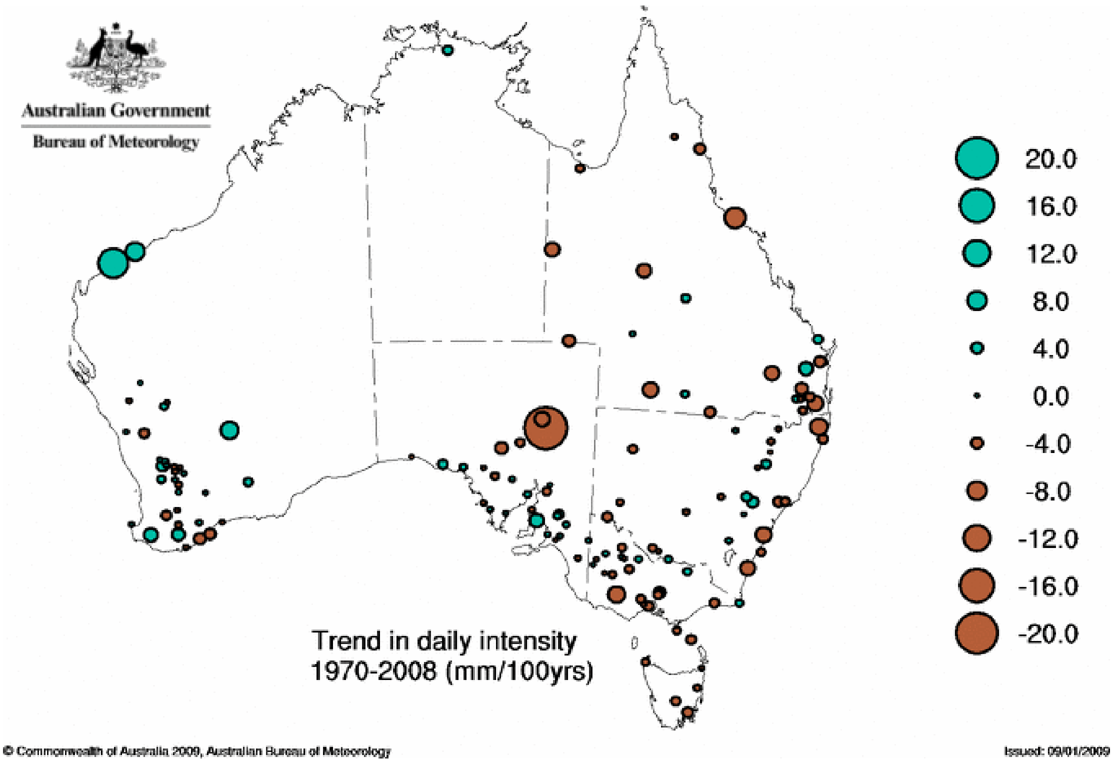


Figure 1.2.15 Annual rainfall intensities from BoM website (http://www.bom.gov.au/cgi-bin/climate/change/extremes/trendmaps.cgi).

Across the south-west there is a minimal decline in the intensity of rainfall from 1950 (Figure 1.2.15a), but since 1970 there appears to be a distinction between the south coast, which continues to see a decline and stations within the SWWA central region, which are showing an increase in intensities. For stations in the far south-west this measure will probably refer to winter changes, but further inland, it may be blurred by the summer signal. Thus, it makes sense to delineate by season.

Rainfall intensities can also be explored by assessing whether days on which particular totals of rainfall have become more or less frequent. Li et al. (2005) and Ryan and Hope (2006) examined this question using two different approaches across the decline in the late 1960s. In Ryan and Hope (2006), the change in the frequency of daily winter rainfall totals in different ranges was explored and at a number of stations, while very light rainfall increased, higher totals decreased, contributing strongly to the declines in totals.

Many studies have explored trends in extreme rainfall across SWWA (Alexander and Arblaster, 2009: Alexander et al., 2007: Aryal et al., 2009: Gallant et al., 2007 and Haylock and Nicholls, 2000). Some divide along seasons (Alexander et al., 2007 and Gallant et al., 2007), but, since the rainfall decline in the south-west was particularly in May, June and July, here we divide our seasons into two winter halves: May to July and August to October, and then, due to the lack of rain-days in summer, the whole summer half year: November to April.

Trends in the total rainfall above the 95th percentile (using only raindays) were calculated. A range of methods were used, but that comparison is not yet complete, thus only simple linear trends will be shown now. The value of the 95th percentile during the 1961-1990 standard WMO climate period are shown in Table 4.

Table 1.2. 4 The 95th percentile for each high-quality station

Peppermint Grove (9594)	**Summer (NDJFMA)**	**Winter (MJJASO)**	**Winter1 (MJJ)**	**Winter2 (ASO)**
Mean Annual Rainfall for 1961-1990 period	201.73	487.18	283.09	212.44
Number of Raindays for 1961-1990 period	1229	2383	1238	1145
95th Percentile cutoff number and value for 1961-1990 period	61 days => 19.2mm	119 days => 21.2mm	61.9 = 62 days => 24.1mm	57 days => 18.3mm
Perangery (8106)	**Summer (NDJFMA)**	**Winter (MJJASO)**	**Winter1 (MJJ)**	**Winter2 (ASO)**
Mean Annual Rainfall for 1961-1990 period	85.22	196.43	137.78	58.65
Number of Raindays for 1961-1990 period	404	1161	705	456
95th Percentile cutoff number and value for 1961-1990 period	20.2 = 20 days => 22.0mm	58.05 = 58 days => 17.8mm	35.25 = 35 days => 20.3mm	22.8 = 23 days => 14.0mm
Wilgarrup (9619)	**Summer (NDJFMA)**	**Winter (MJJASO)**	**Winter1 (MJJ)**	**Winter2 (ASO)**
Mean Annual Rainfall for 1961-1990 period	173.43	656.07	386.89	267.09
Number of Raindays for 1961-1990 period	1214	3304	1754	1550
95th Percentile cutoff number and value for 1961-1990 period	60.7 = 61 days => 17.8mm	165.2 = 165 days => 20.3mm	87.7 = 88 days => 22.9mm	77.5 = 78 days => 18.0mm

Manjimup (9573)	**Summer (NDJFMA)**	**Winter (MJJASO)**	**Winter1 (MJJ)**	**Winter2 (ASO)**
Mean Annual Rainfall for 1961-1990 period	200.44	760.34	456.81	302.72
Number of Raindays for 1961-1990 period	1315	3178	1689	1489
95th Percentile cutoff number and value for 1961-1990 period	68 days => 17.3mm	159 days => 22.4mm	84 days => 25.2mm	74 days => 19.4mm
Doongin Peak (10041)	**Summer (NDJFMA)**	**Winter (MJJASO)**	**Winter1 (MJJ)**	**Winter2 (ASO)**
Mean Annual Rainfall for 1961-1990 period	95.44	228.29	148.20	80.09
Number of Raindays for 1961-1990 period	467	1584	909	675
95th Percentile cutoff number and value for 1961-1990 period	23.35 = 23 days => 22.2mm	79.2 = 79 days => 14.2mm	45.45 = 45 days 17.0mm	33.75 = 34 => 11.0mm
Nyerilup (10541)	**Summer (NDJFMA)**	**Winter (MJJASO)**	**Winter1 (MJJ)**	**Winter2 (ASO)**
Mean Annual Rainfall for 1961-1990 period	123.94	251.64	145.91	102.56
Number of Raindays for 1961-1990 period	675	1751	952	799
95th Percentile cutoff number and value for 1961-1990 period	33.75 = 34 days => 20.0mm	87.55 = 88 => 14.0mm	47.6 = 48 days => 14.7mm	39.95 = 40 days => 12.6mm

Bulong (12013)	**Summer (NDJFMA)**	**Winter (MJJASO)**	**Winter1 (MJJ)**	**Winter2 (ASO)**
Mean Annual Rainfall for 1961-1990 period	113.39	135.84	86.55	49.30
Number of Raindays for 1961-1990 period	512	871	534	337
95th Percentile cutoff number and value for 1961-1990 period	25.6 = 26 days => 20.0mm	43.55 = 44 days => 17.2mm	26.7 = 27 days => 17.3mm	16.85 = 17 days => 17.2mm
Yuna (8147)	**Summer (NDJFMA)**	**Winter (MJJASO)**	**Winter1 (MJJ)**	**Winter2 (ASO)**
Mean Annual Rainfall for 1961-1990 period	79.18	277.05	194.41	85.26
Number of Raindays for 1961-1990 period	453	1547	899	648
95th Percentile cutoff number and value for 1961-1990 period	22.65 = 23 days => 22.9mm	77.35 = 77 days => 17.8mm	44.95 = 45 days => 22.8mm	32.4 = 32 days => 12.2mm
Cape Naturaliste (9519)	**Summer (NDJFMA)**	**Winter (MJJASO)**	**Winter1 (MJJ)**	**Winter2 (ASO)**
Mean Annual Rainfall for 1961-1990 period	134.07	689.67	443.56	246.11
Number of Raindays for 1961-1990 period	1037	3198	1744	1454
95th Percentile cutoff number and value for 1961-1990 period	51.85 = 52 days => 14.4mm	159.9 = 160 days => 21.6mm	87.2 = 87 days => 26.7mm	72.7 = 73 days => 16.0mm

The trends for each season and station will be explored for a period encompassing the strong early winter rainfall decline in the far south-west (1950 to 2007), and they will also be examined for the period since that strong decline.

Table 1.2.5 Trends in station rainfall totals and extremes for summer (November to April) in mm/decade.

Station	Totals 1950-2007	Extremes 1950-2007	Totals 1970-2007	Extremes 1970-2007
Bulong	14.1	4.8	32.8	16.6
Cape Naturaliste	-7.3	-3.7	-5.2	-2.2
Doongin Peak	1.7	0.4	4.4	3.4
Manjimup	-10.1	-6.1	-2.4	-0.6
Nyerilup	3.3	2.2	9.1	4.1
Peppermint Grove	6.8	3.6	2.4	7.2
Perangery	0.7	0.4	6.8	2.9
Yuna	-0.1	-1.3	0.5	-1.9

Summer

In all cases except Yuna, trends in the totals and extremes are in same direction (Table 5). However, trends at Yuna are small. For all stations except Peppermint Grove, the trends in totals are larger than for extremes. In the far southwest (Cape Naturaliste, Manjimup), there is a weakening of the declines between the two periods, while the more inland stations (Bulong, Doongin Peak and Perangery) have strengthening increases.

Table 1.2.6 Trends in station rainfall totals and extremes for early winter (May to July) in mm/decade.

Station	Totals 1950-2007	Extremes 1950-2007	Totals 1970-2007	Extremes 1970-2007
Bulong	-0.8	-0.5	-4.5	-4.5
Cape Naturaliste	-14.2	-3.0	-28.7	-2.0
Doongin Peak	-7.8	-1.3	-0.7	3.3
Manjimup	-21.6	-10.2	-21.1	2.1
Nyerilup	-6.5	-1.6	-2.7	-2.3
Peppermint Grove	2.4	1.6	-8.7	-8.4
Perangery	-8.4	-3.0	-1.3	-3.5
Yuna	-10.1	-4.8	-9.4	-4.2

Early Winter

All cases except for Peppermint Grove's 1950-2007 trend are negative. However, the negative trend since 1970 at Peppermint Grove is reasonably strong. Cape Naturaliste and Manjimup have a huge trend in totals during the 1970-2007 period, however they have a minimal trend by comparison in extremes. Yuna, on the other hand, has a big negative trend in totals, half of which is from the extremes.

Table 1.2.7 Trends in station rainfall totals and extremes for late winter (August to October) in mm/decade.

Station	Totals 1950-2007	Extremes 1950-2007	Totals 1970-2007	Extremes 1970-2007
Bulong	2.8	0.8	-3.5	-3.7
Cape Naturaliste	2.5	4.4	-1.7	4.2
Doongin Peak	2.2	0.4	-2.7	-1.2
Manjimup	4.2	4.1	10.4	7.9
Nyerilup	0.5	-1.6	5.9	1.6
Peppermint Grove	1.7	0.3	-6.6	-7.0
Perangery	3.4	-0.2	2.1	-2.0
Yuna	4.4	2.4	-0.1	-0.9

<u>Late Winter</u>

Late winter has more trends similar in magnitude between totals and extremes compared to summer. There is very little in terms of a signal, the only reasonably large magnitude cases are increases at Manjimup, strengthening in the more recent period, and decreases at Peppermint Grove since 1970.

Discussion

The drying trend in spring since 1970 (Figure 3) is in agreement with the trends suggested by climate models forced with enhanced levels of atmospheric greenhouse gases (Bertrand Timbal, pers. comm., 2008). However, Figure 3 is not in agreement with the trends found for Manjimup and Nyerilup for 'late winter' (August to October) in Table 7– suggesting either that the months that differ between these two seasons result in altered trends, or Figure 3 is based on different station data. Figure 7 reveals that there were upward trends in August and September, but downward trends in October and November. This highlights the importance of examining the data closely to avoid misinterpreting the trends seen. It was believed that the suggested response in climate models in spring should be explored more completely, and this extra work will replace the development of a synoptic classification method for autumn, and be reported on in the next annual report.

In Milestone 1.2.1 high-pressure synoptic patterns had increased in their daily June and July number in the last decade. The rainfall anomaly patterns associated with those synoptic types has particularly dry conditions along the west coast, but minimal signal along the south. The analysis for Milestone 1.2.1 only examined June and July, so there may be another component to the rainfall declines in May. Nicholls and Lavery (1992) found that the stations along the south coast fell into a different category than the rest of SWWA when they clustered regions together based on similarities in the variations of their annual rainfall cycle.

The relationship between the magnitude of the trends in totals and extremes at Manjimup for early winter suggests that the decrease through the 1960s was due to a loss of extreme daily rainfalls, but the recent declines were due to declines from days across all rainfall intensities.

References

Alexander LV and Arblaster JM, (2009) Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. *International Journal of Climatology*, **29,** 417-435.

Alexander LV, Hope P, Collins D, Trewin B, Lynch A, and Nicholls N, (2007) Trends in Australia's climate means and extremes: a global context. *Australian Meteorological Magazine*, **56,** 1-18.

Aryal SK, Bates BC, Campbell EP, Li Y, Palmer MJ, and Viney NR, (2009) Characterizing and modeling temporal and spatial trends in rainfall extremes. *Journal of Hydrometeorology*, **10,** 241-253.

Emori S and Brown SJ, (2005) Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate. *Geophysical Research Letters*, **32,** L17706.

Gallant AJE, Hennessy KJ, and Risbey J, (2007) Trends in rainfall indices for six Australian regions: 1910-2005. *Australian Meteorological Magazine*, **56,** 223-239.

Haylock M and Nicholls N, (2000) Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910-1998. *International Journal of Climatology*, **20,** 1533-1541.

Hope P and Foster I, 2005: How our rainfall has changed - The south-west. *Indian Ocean Climate Initiative, Climate Note 5/05*, Indian Ocean Climate Initiative, Perth, Australia.

Hope P, Timbal B, and Fawcett R, (2009) Associations between rainfall variability in the southwest and southeast of Australia and their evolution through time. *International Journal of Climatology*.

IOCI, 1999: *Towards understanding climate variability in south western Australia - Research reports on the first phase of the Indian Ocean Climate Initiative*. *Technical Report*, Indian Ocean Climate Initiative Panel.

IOCI, 2002: *Climate variability and change in south west Western Australia*. *Technical Report*, Indian Ocean Climate Initiative Panel.

Jones DA and Weymouth G, 1997: An Australian monthly rainfall dataset.

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

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

Li Y, Cai W, and Campbell EP, (2005) Statistical modeling of extreme rainfall in southwest Western Australia. *Journal of Climate*, **18,** 852-863.

Nicholls N and Lavery B, (1992) Australian rainfall trends during the twentieth century. *Int. J. Climatol.*, **12,** 153-163.

Ryan B and Hope P, Eds., 2006: *Indian Ocean Climate Initiative Stage 2: Report of Phase 2 Activity*. *Technical Report*, Indian Ocean Climate Initiative Panel, 37 pp.

Samuel JM and Sivapalan M, (2008) A comparative modeling analysis of multiscale temporal variability of rainfall in Australia. *Water Resources Research*, **44,** W07401.

Srikanthan R, James RA, and Matheson MJ, 2002: *Evaluation of the performance of the tipping bucket rain gauge under field conditions. Final Report.* Hydrology Unit, Bureau of Meteorology, Melbourne, 64 pp.

Viney NR and Bates BC, (2004) It never rains on Sunday: the prevalence and implications of untagged multi-day rainfall accumulations in the Australian high quality data set. *International Journal of Climatology*, **24,** 1171-1192.

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