Climate variability and change in south west Western Australia

Indian Ocean Climate Initiative

Perth, September 2002

Abstract

This report integrates the understandings of climate variability and change for south western Australia developed over a five year program of strategic research under the auspices of the Indian Ocean Climate Initiative (IOCI).

IOCI is a strategic program of research and information transfer aimed at supporting decision-making in climate affected industries. Research directed at developing inter-seasonal forecasting and better understanding climate variability on longer time-scales became progressively focussed on issues of decadal variability and climate change because of the dominance of these issues in any analyses of the observed record.

Key findings include:

- *Winter rainfall has decreased sharply and suddenly in the region since the mid 70s.*
- *The decline was not gradual but more of a switching to an alternative rainfall regime.*
- *The rainfall decrease accompanied and was apparently associated with, documented change in large scale atmospheric circulation at the time.*
- *The decrease in rainfall, and associated circulation changes, bear some resemblance to model projections for an enhanced greenhouse effect (EGE) but are not sufficiently similar to indicate, beyond doubt, that the EGE is responsible.*
- *Most likely both natural variability and the EGE have contributed to the rainfall decrease.*
- *The climatic shifts, which include warming have resulted in an even sharper fall in regional streamflows.*
- *Findings have altered previous interpretations of the climate of the region and decision-makers need to alter their decision base-lines to reflect observed and projected changes but also to include increased levels of uncertainty.*
- *The changing climate will exhibit wetter and drier periods throughout the 21st century due to natural variability, overlaid on trends of continued warming and of probable decline in mean rainfall consequent on the EGE.*
- *A major scientific challenge is to further determine the relative influences of natural multi-decadal variability and the EGE in contributing to the recent decrease in rainfall.*

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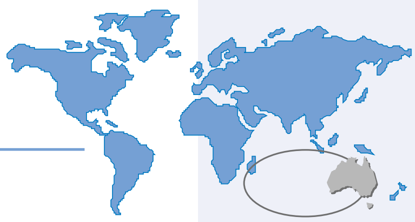

A contributing partnership
in climate research ~ January 1998

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IOCI

A partnership, formed by the WA State Government, to establish such knowledge of

- Climate variability.
- Climate change.

as is needed to support informed and effective climate adaptation.

Core Research Team

Bureau of Meteorology Research Centre
CSIRO Atmospheric Research
CSIRO Land and Water
CSIRO Mathematical & Information Sciences

Perth, September 2002

Foreword

This report draws together five years of study of climatic variability in south-western Australia. It is written specifically to interpret that work for the benefit of decision-makers in climate affected industries and in natural resources management of the region.

The IOCI Panel has very actively directed this research program and its associated workshops and debates over the past five years. Having travelled that path, the Panel is unanimously convinced that the natural and human induced changes to regional climate and climate variability, discussed herein, demand serious attention by decision-makers. This need for action relates to a range of industries and resource management sectors.

The south-west of Australia has long enjoyed a reputation as a region of reliable rains. Thanks to the Leeuwin current, it enjoys the most well-watered climate of mid-latitude, west-coastal regions in the world. However, this characteristic reliability has been brought into question by the sustained drought of the last quarter century.

National and international research of global warming suggest this region will lead a significant rainfall decrease in southern Australia over coming decades. However, whether or not enhanced greenhouse effects have been implicated, the experience of the last quarter century now demands a revision of planning baselines. Projections of enhanced greenhouse effects impose an escalating demand for adaptive management but it must be remembered that they are not the sole cause of that demand.

Predictive climate science is difficult. Technical limitations and statistical uncertainties overlay one another. However, the science is advancing rapidly. This report draws on such advances but still finds important questions unresolved. In reality, both climate and science are evolving together, the former more quickly than gives room for complacency.

Change is already with us, and further change is inevitable. Some changes may offer benefits, rather more may threaten losses. Benefits will not be fully realised nor losses minimized without adaptive responses, and decision-makers must make judgements. IOCI's role, present and future, is to help such judgements exploit developing climate science and keep pace with evolving climate change.

This report is an important integration of current understanding of climate variability and change in the region. Many people have contributed to its creation, both from within the strategically directed research program of IOCI and from outside the IOCI team. Indeed, the latter contributions, which have been made generously, have been an important aspect of IOCI's learning and an added source of material captured in this report.

This report was prepared for IOCI by Dr. Neville Nicholls in collaboration with other research members and in consultation with the full Panel. The Panel is greatly indebted to Neville for the commitment and climatological insight he has contributed to the report.

Brian Sadler
Chair, Indian Ocean Climate Initiative Panel

Executive Summary

Has the climate of the Southwest changed?

- Winter rainfall in the southwest of Western Australia has decreased substantially since the mid-20th century. This has altered the perceptions of regional climate even though a similar, albeit less severe, dry sequence was experienced earlier in the century.
- The recent rainfall decrease was only observed in early winter (May-July) rainfall; late winter (August-October) rainfall has actually increased, although by a smaller amount.
- The winter rainfall sharply and suddenly decreased in the mid-1970s by about 15-20%. It was not a gradual decline but more of a switching into an alternative rainfall regime.
- The reduction in winter rainfall resulted in an even sharper fall in streamflow in the southwest.
- Temperatures, both day-time and night-time, have increased gradually but substantially over the last 50 years, particularly in winter and autumn.

What caused the change?

- The rainfall decrease accompanied, and was apparently associated with, a well-documented change in the large-scale global atmospheric circulation at this time.
- The decrease in rainfall, and the associated circulation changes, bears some resemblance to changes most climate models project for an enhanced greenhouse effect.
- However, the changes are not sufficiently similar to indicate that the enhanced greenhouse effect is responsible, beyond reasonable doubt, for the rainfall decrease. This decrease may simply reflect natural climate variability. Most likely, both natural variability and the enhanced greenhouse effect have contributed to the rainfall decrease.
- Other local factors, such as land-use changes in the southwest, or increased local air pollution, seem unlikely to be major factors in the rainfall decrease, but may be secondary contributors. Global land use changes and ozone depletion may also have played a role in the climate change in the southwest.
- The 20th century warming in the southwest is believed to be largely the result of the enhanced greenhouse effect.

What should we assume about the future climate?

- The climate of the southwest will continue to exhibit wet and dry periods throughout the 21st century due to natural climate variability, overlaid by changes expected from enhanced greenhouse conditions. The latter include a likely continued warming coupled with the probability of a decrease of winter rainfall.
- It is difficult, at this stage, to provide more definitive recommendations regarding what 'base-line' climatology, particularly for rainfall, should be used in decision-making. This is because of inherent scientific uncertainties and because different risk-structures will be associated with various decision sectors.
- Decision makers will need to consider a range of more specific planning scenarios around these general expectations. These need to take into account alternative greenhouse gas emission scenarios recently published by the IPCC and interpreted nationally by CSIRO.
- The major scientific challenge, if we are to provide more definitive projections of the climate of the southwest, is to determine the relative influences of natural variability and the enhanced greenhouse effect in causing the recent decrease in rainfall.

Can we make short-term climate predictions?

- Attempts to improve the short-term climate predictions in the southwest have been frustrated, in part, by the difficulty in predicting the behaviour of the El Niño – Southern Oscillation across the March-May period. This is the time when forecasts would be most useful, but it is also the period when forecasting is most difficult almost everywhere. Multidecadal variations in the association between the El Niño – Southern Oscillation and southwest rainfall have also contributed to the difficulty in developing useful climate prediction systems.

- Targeted short-term climate predictions have been developed for the region. These show moderate skill for some variables and seasons. In particular, prediction of spring and summer temperatures (and to a lesser extent, rainfall) appears feasible for the southwest. These predictions might be used to enhance the operations in economic sectors affected by temperature (e.g., water demand management).

Introduction

A sustained reduction of the usually reliable cool-season (May-October) rainfall in southwestern Australia (the southwestern area is delineated in Figure 1) over recent decades (Figures 2, 3) has challenged the assumption that climate-affected industries in the region should use the past climate record for planning.

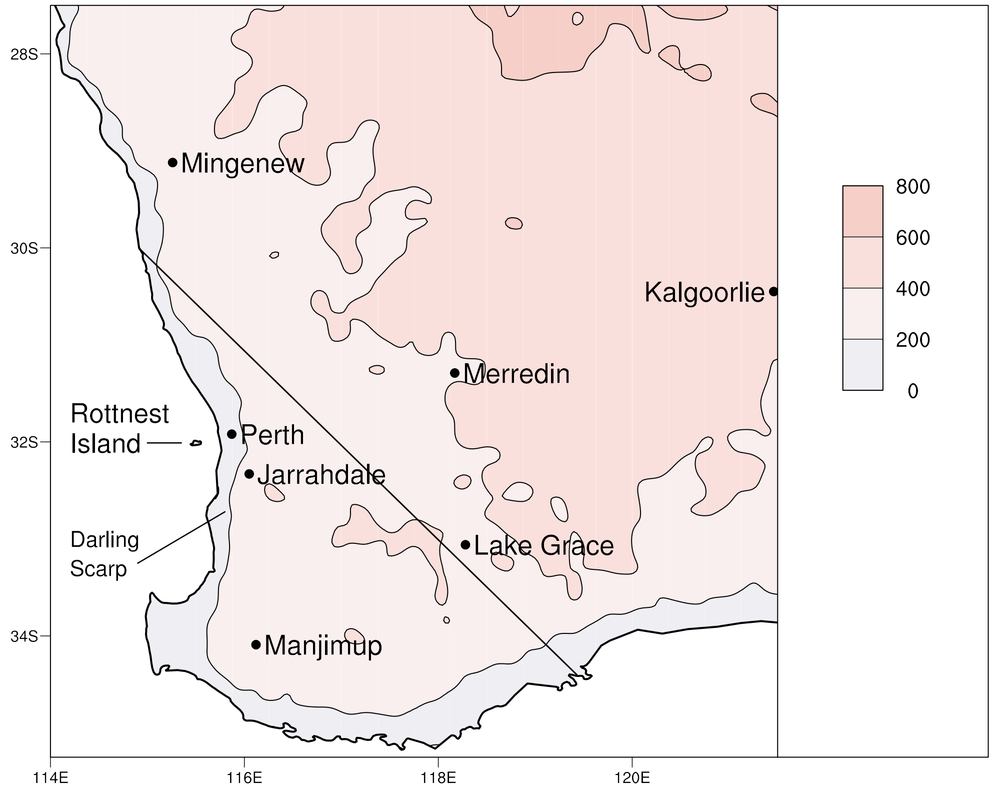


Figure 1 Location of stations and area defined as 'SWWA' (region southwest of line). Elevations (metres) contoured and coloured.

Should climate-affected industries assume that the lower rainfall of recent decades will continue, or can they assume that rainfall might return to the higher levels observed in the middle decades of the 20th century? Can we predict the likely level of rainfall over the next few decades, from either past behaviour, or physical and statistical reasoning? Such a prediction could impact substantially on planning for the region, as would a forecast, each year, of rainfall for the imminent winter.

> With low summer humidity, sufficient rainfall, and temperature climate, the region of Swanland is undoubtedly one of the healthiest in the world for people of our race.
>
> Griffith Taylor, *The Australian Environment (Especially as controlled by rainfall)*, Memoir No. 1, Advisory Council of Science and Industry, Commonwealth of Australia, 1918, 188 pp.

If such forecasts are to be credible we would first need to identify the likely cause of the observed decrease. Average May-October rainfall in the southwest in the last 25 years has been only about 85-90% of the preceding 50-year average (Figure 2).

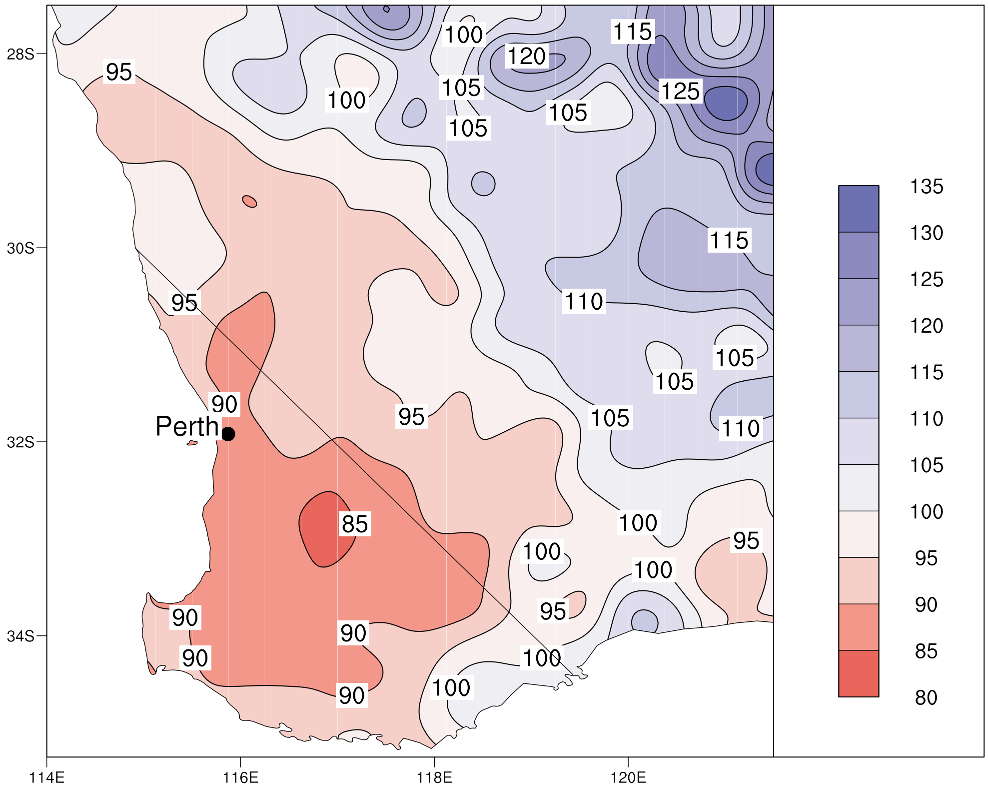


Figure 2 Average May-October rainfall over the 1976-2001 period as a percentage of the average May-October over the 1925-1975 period.

The portion of this decrease that has occurred since the middle of the 20th century has been confined to the early winter (May-July) rainfall, while rainfall later in the season (August-October) has increased (Figure 3). This increase in August-October rainfall is a return to higher levels after rainfall at this time of year had decreased strongly in the first half of the 20th century. What does the fact that the recent decrease has been in early winter tell us about the likely cause of this decrease? Does it suggest that the decrease may be linked to local changes in the frequency or intensity of synoptic systems affecting the southwest? Can these changes be linked with human behaviour such as local or regional air pollution or the enhanced greenhouse effect?

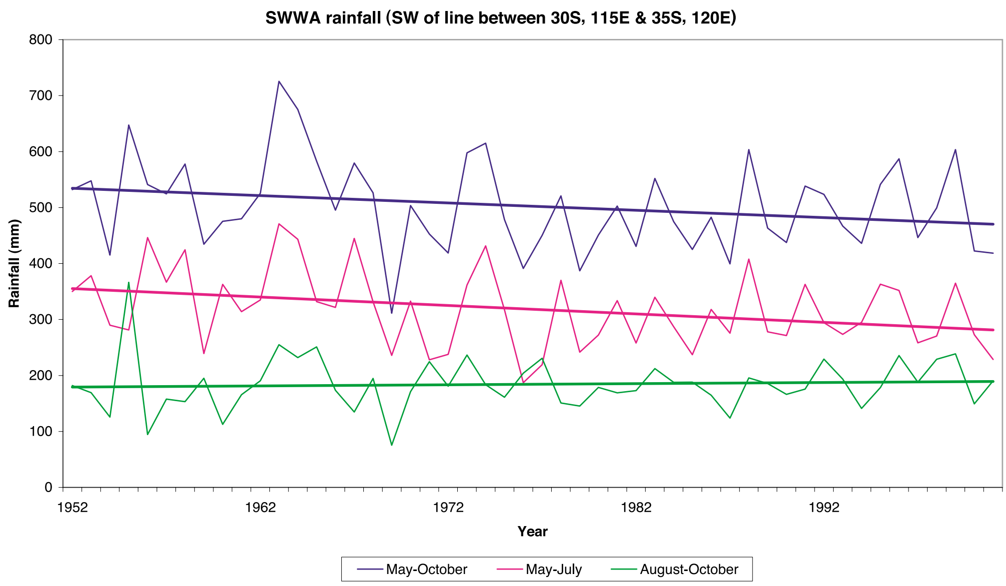
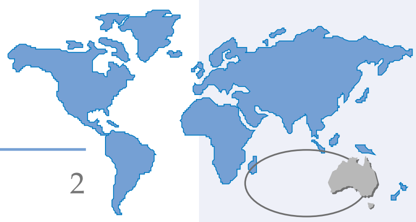


Figure 3 SWWA rainfall (Southwest of line connecting 30S, 115E & 35S, 120E).



A single station example, from Rottnest Island Lighthouse (Figure 4), provides a longer perspective of the recent decrease in early winter rainfall. Horizontal lines on this figure indicate the mean May-July rainfall for three periods: 1880-1920, 1921-1975, 1976-1995 (the station was closed in December 1995). The last two decades have been dry in early winter, especially compared with the previous half-century. Although the decades just before and after the start of the 20th century were relatively dry, they were still wetter than the most recent period.

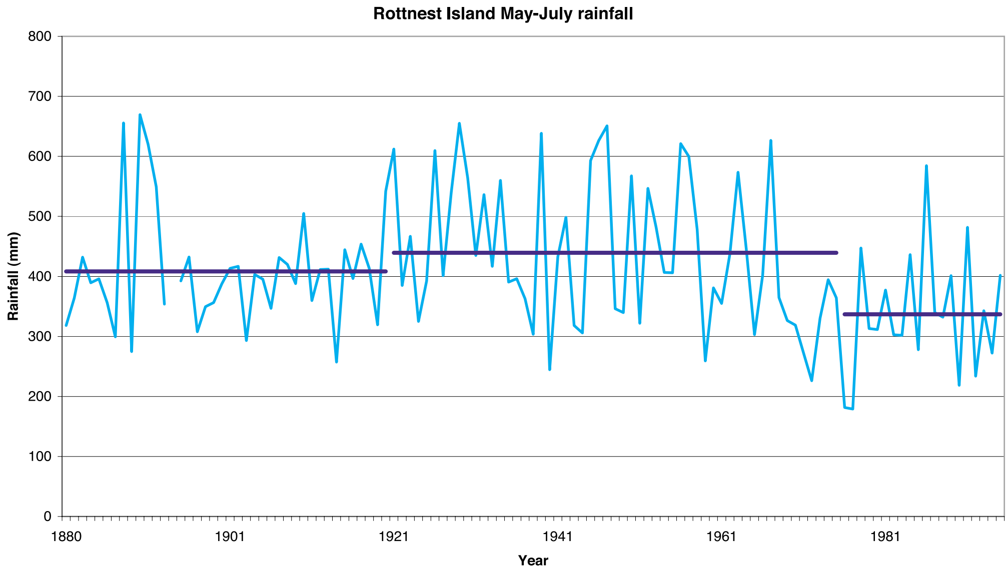


Figure 4 Rottnest Lighthouse May-July rainfall, 1880-1995. Horizontal lines are means for 1880-1920 (408mm), 1921-1975 (439 mm), and 1976-1995 (337mm).

Extreme daily rainfalls have become rarer. Statistical analysis of daily rainfall has revealed how strong this decline in extreme rainfall events has been. Table 1 lists the probability of exceeding a range of various extreme daily rainfall amounts at Manjimup, comparing 1930-1965 versus 1966-2001. There has been a substantial decline in the probability of large daily rainfall events – such events have become much rarer. The break point in 1966 was chosen from a detailed statistical analysis of the distribution scale and shape parameters. There have been some significant variations in these parameters over the period of record, but the period since about 1966 is notably consistent suggesting a stable distribution for extreme rainfall at the current reduced levels since then.

Table 1 *A comparison of exceedance probabilities for extreme daily rainfall in 1930-1965 and 1966-2001, at Manjimup.z*

Daily rainfall (mm)	Probability (1930-1965)	Probability (1966-2001)
30	0.0132	0.00472
34	0.00837	0.00281
38	0.00543	0.00167
40	0.00448	0.00129
50	0.00181	0.000363
60	0.000835	0.000363

For hydrological systems of the region, particularly rivers, wetlands and shallow groundwaters, the impact of the decrease in rainfall has been exacerbated by the concurrent increase in both maximum and minimum temperatures through winter (Figure 5). This warming presumably has increased evapo-transpiration and consumption, at a time when water supply inflow was decreasing and population pressures were increasing. The warming has probably contributed to the reduced inflow through increased evapo-transpiration on catchments. However, water supply demand is strongest during summer, and mean maximum daily temperature has not increased at this time of year. Mean minimum overnight temperatures in summer have increased, but much less strongly than the winter overnight minimum temperatures. Thus increased water supply demand, over the year, is less than might have been the case if summer temperatures had increased as strongly as have winter temperatures.

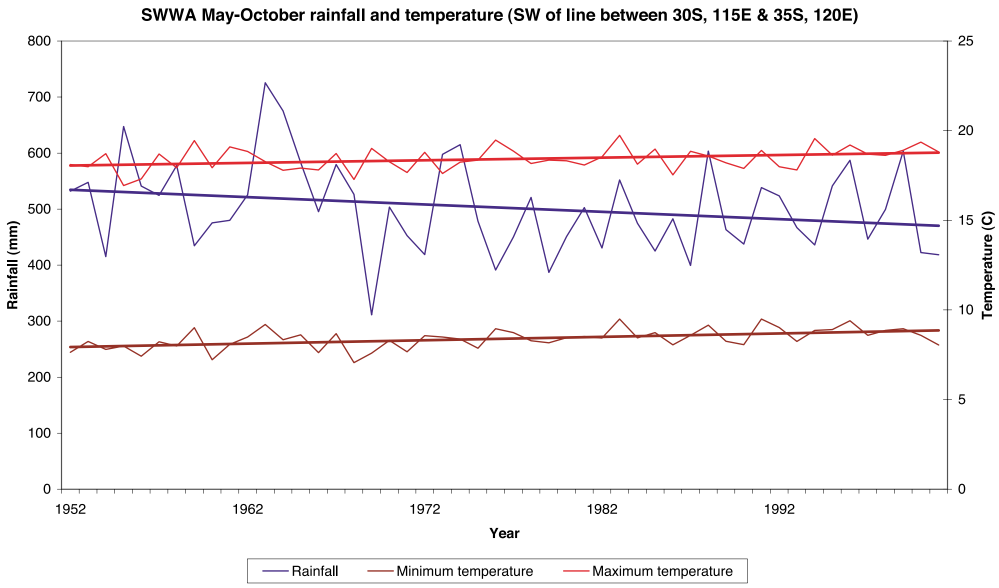


Figure 5 SWWA May-October rainfall and temperature (SW of line between 30S, 115E & 35S, 120E).

The implications of the decrease in rainfall can be illustrated by the development of the Perth water system. In the mid-1980s water resource managers and planners became concerned by the observed decrease in inflows into Perth reservoirs relative to the mean inflow during the last few decades (Figure 6). Expected inflows were adjusted downwards, and these lower expected flows were used in timing new water source augmentation. As the reduced rainfall continued into the early 1990's further adjustments were made to the timing of new water sources and in 1995 strategic plans proposed for 'Perth's Water Future' were based on streamflow averages heavily weighted towards the recent decades. In 1996, following a Climate Variability and Water Resources Workshop the design basis for surface water sources was again radically adjusted downwards to inflows based solely on the dry quarter century. At least part of the reason for this design decision was a statement from that workshop that *it is now the responsibility of the Corporation to review its position on climate change, climate variability and source development in view of the continuing period of historically low streamflows over the last two decades.* It is also noteworthy that at least part of the background to the 1996 design judgement was a workshop recognition that longer term fluctuations may occur as *jumps* rather than *smooth* trends. The 1996 design adjustment resulted in the accelerated development of new water sources, having a current cost of some $500 million, as well as sharpening initiatives to reduce demand through water use efficiency measures. This reduction is also challenging the management of regional wetlands and water allocation.

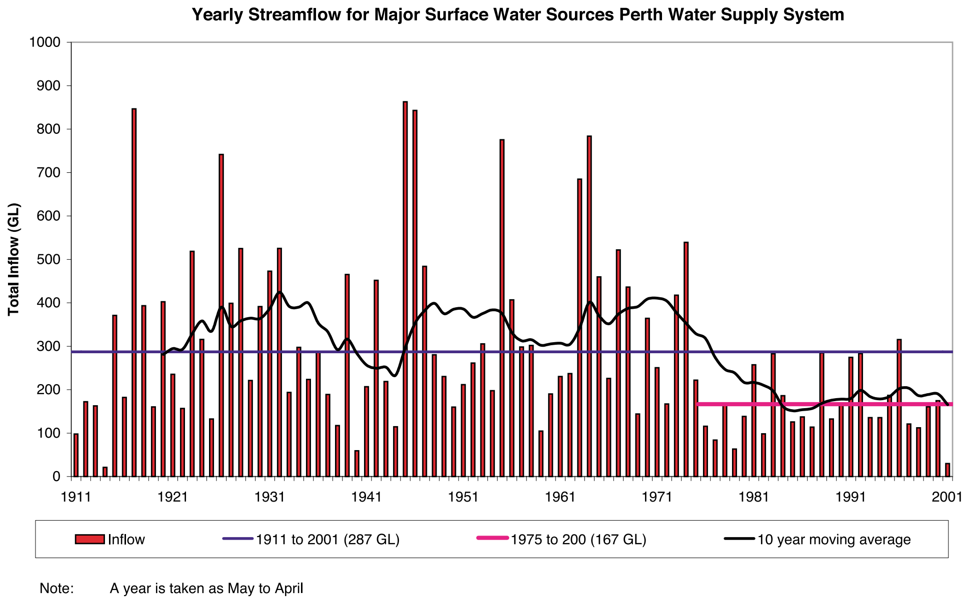


Figure 6 Yearly input into Perth water supply.

Looking beyond the example of water, there is a growing belief through the region that recent low rainfalls have been too persistent to be classed as 'anomalies'. Many people are now thinking that what was previously called 'dry' is more like 'normal' nowadays. There is increasing acceptance that the most relevant climate statistics may be those of the past three decades, rather than earlier times. Agricultural and other systems are being reviewed as to their suitability to the current climate. There are profound implications, for nature conservation, farmers, farm-based industry, forest managers, water users, water providers, business and Government.

Improved understanding of the cause of the recent rainfall decrease, or predictions of whether rainfall might continue to be low relative to historical values, will be useful in future planning of water resource development and other climate-affected planning. What about shorter-range climate predictions? For some parts of the world, e.g., eastern Australia, systems have been developed that enable potentially useful seasonal climate forecasts to be prepared with lead times of a month or two. Can forecasts with levels of skill substantially greater than those currently available be produced for southwestern Australia? If so, these may also assist in planning for climate-affected industries and natural resource management.

Here we summarise the results of the Indian Ocean Climate Initiative (IOCI), a research initiative of Western Australian government agencies to enhance decision-making affected by the climate variability of the southwest, the region of declining rainfall. The IOCI, launched in 1998, has improved understanding of the causes and predictability of the climate variations in the region. A general overview of the climate of the region is first provided, before we address the question of predicting the climate in the southwest. The focus is on cool-season or winter (May-October) rainfall, and especially May-July rainfall, because of the concerns with the decrease in this variable in recent decades. We also report on efforts to improve temperature forecasts, as well as rainfall forecasts, and for spring and summer as well as for winter. Improvements in forecasts of these variables and seasons could improve management in climate-affected sectors including agriculture, water supply and conservation, and fire hazard control. More detailed descriptions of some of the work discussed here are available in research reports published earlier by IOCI (IOCI, 1999, 2001).

Climate is ever-changing – evidence from the past

Climate is not constant. The Intergovernmental Panel on Climate Change (IPCC) has documented the large-scale changes in climate over the Northern Hemisphere over the past 1000 years (Folland et al., 2001), and concluded that "An increasing body of observations gives a collective picture of a warming world and other changes in the climate system". The paucity of historical temperature records and proxies for prehistorical climate, such as tree-rings, preclude a similar exercise for the Southern Hemisphere, at this time. However, the large-scale changes in Northern Hemisphere climate probably illustrate the scale of the changes that may have occurred in the Southern Hemisphere.

> "The wet season commences with light showers in April, which continue to increase in number and force throughout May, June, and July, and from that period to decrease until they cease altogether, in the month of November, when the dry weather begins… The extreme drought and heat of an Australian summer render it the less agreeable portion of the year; whilst the winter, with the exception of intervals of stormy weather, is only sufficiently cold to be pleasant… In the winter season gales of wind from the N.W. and S.W. are very frequent, and are usually accompanied by heavy falls of rain… At such periods the atmosphere is charged with moisture to a considerable degree, and the quantity of rain that has been ascertained to fall at King George's Sound in the course of the six winter months equals the quantity experienced in the western counties of England."
>
> Wells, W. H., *A geographical dictionary: or gazetteer of the Australian colonies: their physical and political geography*, Sydney, 1848.

The best-documented change is the gradual cooling of the Northern Hemisphere from about 1000 years ago to the end of the 19th century, followed by the rapid rise in temperature during the 20th century. The recent rise appears to have been stronger than any other hemispheric temperature change in the previous 900 years. On a regional scale, Europe appears to have been relatively warm early in the last millennium (the 'Medieval Warm Period') and then relatively cool between the 15th and 19th centuries ('The Little Ice Age'). Variations in regional rainfall probably accompanied such regional variations in temperature.

On these longer time-scales, large variations in regional climate may occur. However, Wyrwoll et al. (2000) suggest that major changes, especially decreases in winter rainfall, have not occurred in the southwest over the past 20,000 years. Such a change would have substantially altered the dominant vegetation which is linked to the high annual rainfall. With no significant refuges or opportunities for 'migration', any substantial decrease in rainfall would have caused a substantial change in vegetation.

The lessons for interpreting the recent rainfall decrease in the southwest, from studies in areas where data allow the estimation of climate changes over the last millennium, are that:

- Climate changes and varies, even in the absence of human influence.
- On a regional scale these changes can be quite noticeable.
- The recent global warming is likely to have been much stronger than previous changes in the recent historical past.

How likely is it that the recent rainfall decrease in the southwest is just part of the natural variability of climate? We have several ways of approaching this question. Using rainfall data from the past 100 years, it is possible to estimate how unusual the recent decrease in rainfall in the southwest has been, ie., how likely it is that the decrease is part of the natural variability of climate. Such an analysis suggests that the recent run of dry years is very unusual (IOCI, 1999). Thus it seems unlikely (although not impossible) to have been caused solely by a random event associated with natural variability of the climate.

However, Gentilli (1971) pointed out that winter monthly rainfalls at Perth had increased by between 3% (August) and 42% (June) between 1877 and 1947. So, the recent decrease may be returning winter rainfall to levels similar to the late 19th century, after a relatively wet period in the middle decades of the 20th century (see also Figure 4 ~ refer page 3). Further evidence that the recent dry period could reflect just natural variability comes from climate model studies. Similar runs of dry years (to those observed in the southwest recently) were found in a 1000-year model simulation for present-day conditions, although they were uncommon. So it is feasible that the current dry conditions are simply a part of the natural variability of climate. This possibility is considered again later, however it should be noted here that 'natural variability' does not simply equate with 'random'. There can be, even without external forcings, long periods of dry (or wet) conditions in regional climate, due to the internal interactions in the climate system. So, even if it were concluded that the observed decrease was likely due to natural variability, this would not mean that we could assume it would return to something like 'normal' rainfall in the near future. On the other hand, neither could we assume that the rainfall would continue to be low for the foreseeable future.

The climate of the southwest – a reputation for reliability

> The most reliable rainfall occurs in the extreme south-west between Perth and Leeuwin. Here the rains rarely vary 10 per cent. from their average amount, and the lot of the farmer should be a happy one.
>
> Griffith Taylor, *Australian Meteorology*, 1920.

William Stanley Jevons conducted the first comprehensive, scientific study of the Australian climate, in 1859. Jevons observed that "the Australasian climate is one of irregular rains, and is thus distinguished from most climates where the rains are pretty equable and constant although less in total amount". He noted that Western Australia (or at least the southwest) did not appear to suffer from the long droughts that were typical of the rest of Australia, so that "we may perhaps conclude, that the climate of this part, shows less variations in the yearly rainfall than the climate of the other colonies". Recent work has confirmed that the annual rainfall is indeed less variable in the southwest corner of the country, relative to other parts (Nicholls et al., 1997).

Much of the rainfall of the southwest falls during the cooler season, from May to October. Wright (1997) notes that over 80% of annual rainfall in the southwest falls in this period. Within this region, there is a marked gradient in total winter rainfall from east to west (Figure 7), and a gradient in temperature from south to north. Wright (1974a) describes the winter rainfall of the southwest thus:

> "From south to north, there is a rapid decrease of rainfall with distance over the first 80 km followed by a much slower, steady decrease. From west to east the rainfall increases with distance inland over the first 30 km or so, especially in the south over the Darling Scarp, and then decreases steadily."

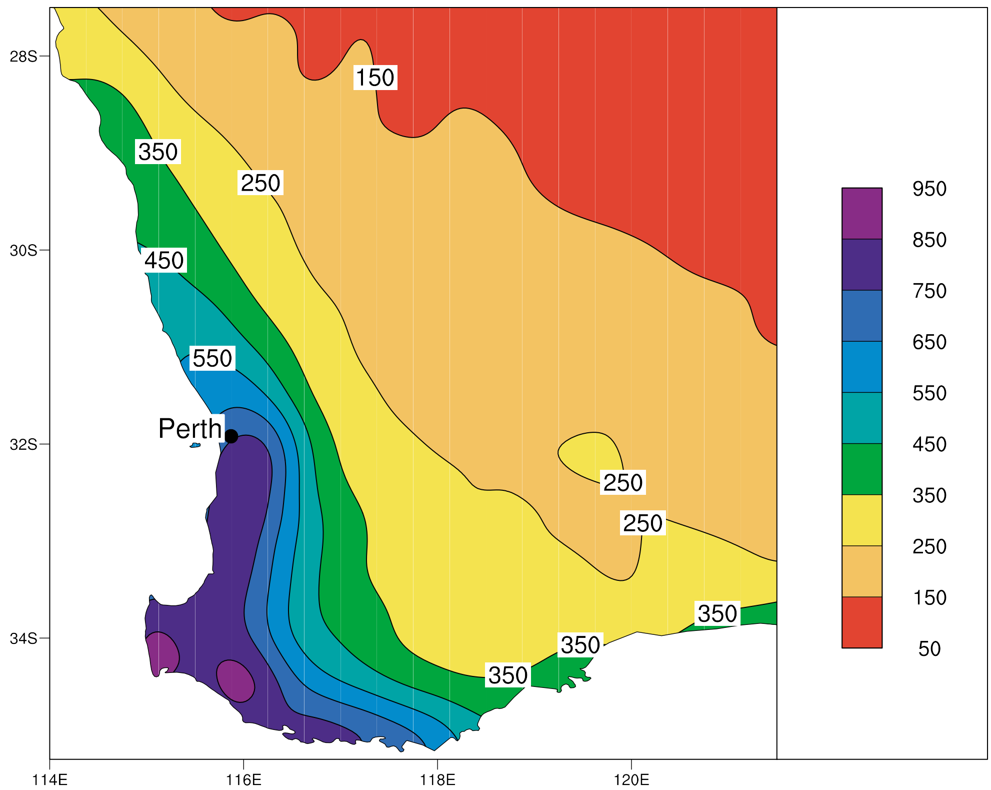


Figure 7 Mean May-October rainfall (mm), 1900-2000.

Perth clearly has a reliable rainfall, which repeats its pattern of a well-marked winter rainfall, with considerable constancy.

Griffith Taylor, 1940. *Australia. A study in warm environments and their effect on British settlement*. Methuen, London, p 68.

Late winter (August-October) rainfall tends to be lower than earlier (May-July) rainfall (Figure 3 ~ refer page 2), especially in the north of the region. This decrease in the late part of the cool season tends to be weaker where the rainfall is most enhanced by the effects of orography and coastal friction, or where stations are relatively sheltered from northwesterly and westerly winds.

Mechanisms governing the southwest climate – cold fronts and cloudbands

Generally, the western edges of landmasses receive rather low rainfall, partly because most oceans have a current flowing toward the equator along their eastern boundary. This cool current reduces the atmospheric moisture available to the region. In Perth, however: "The availability of copious moisture and the lack of a cool off-shore current, combined with the great force of the wind (Perth is the windiest Australian city), give this region a plentiful rainfall, nearly double that of any similarly exposed localities in any other continent, and a longer rainy season." (Gentilli, 1972).

> As Perth averages nearer to 35 than 34 inches per annum, most of which is concentrated into six or seven months of the year, the winter is, of course, wet, and the rain sometimes depressingly persistent. However, the fine intervals compensate by being really fine, sharp mornings, sometimes frosty, and brilliant sunshine all day, perhaps only for a day or two, perhaps for a week or even longer.
>
> E. B. Curlewis, "The climate of Western Australia", in H. A. Hunt, *Results of rainfall observations made in Western Australia*, Government Printer, Melbourne, 1929.

The annual cycle of heavy winter rainfall and low summer rainfall is the result of the annual cycle of the planetary winds (Gentilli, 1972): "The subtropical belt of high pressure extends across this region during the summer months, reaching its southernmost extension in January or February. During the autumn it gradually moves towards the north and lies almost wholly outside the region during the winter months. In the spring a gradual southward shift occurs …".

The sub-tropical high-pressure belt is composed of successive anticyclonic cells, located over the Indian Ocean and the Australian continent. Northwesterly winds bring heavy rains in winter (Wickham, 1846): "Wintry storms come in with a north-west wind. This rushes down, laden with the moisture of the warm Indian Ocean, which it deposits with more rudeness and racket than the inhabitants can applaud. The gale begins north-north-east, veers west, and blows its hardest between west-north-west and west-south-west."

Wright (1974a) notes that the "… winter rainfall is largely associated with moist unstable westerly winds and with progressive troughs within the westerly airstream. The mean depression track and the associated zone of maximum rainfall are always south of the region, accounting for the decrease of rainfall from south to north. The unstable westerly airflow produces heavy showery rains; these are enhanced by the high ground of the Darling Scarp and by convergence induced by friction on the air as it reaches the land, so accounting for the pattern near the west coast. Farther eastward, the moisture content becomes depleted with increased land track, leading to the steady decrease in rainfall."

Wright (1974a) reported that two fundamental types of winter rain affect the region: Type 1 is generally continuous rain associated with an upper tropospheric jet stream from north of west and widespread ascent in the mid troposphere, usually associated with a surface wind between west and north. This situation is commonly associated with the approach of a cold front, where relatively warm, humid air is drawn southwards from the Indian Ocean. The amount of rain in this type does not differ greatly from north to south, there is little coastal enhancement, and the amount of rainfall decreases with the length of the track of the airstream over land.

Type 2 is showery rain associated with convection in a moist unstable airstream, usually during and after the passage of a cold front. This type is probably more frequent with west to southwest winds. The intensity of rain in this type normally decreases from south to north. The rains are greatly enhanced by coastal friction and orography, and decrease rapidly with distance inland. There is a marked decrease in Type 1 rain from early in the winter to later in the season, but little decrease in Type 2 rains. Figure 8 shows that in the late winter, much less rain is associated with northwest winds relative to earlier in the season, whereas rain in the late winter associated with southwest winds is only slightly less than that associated with such winds earlier in the year.

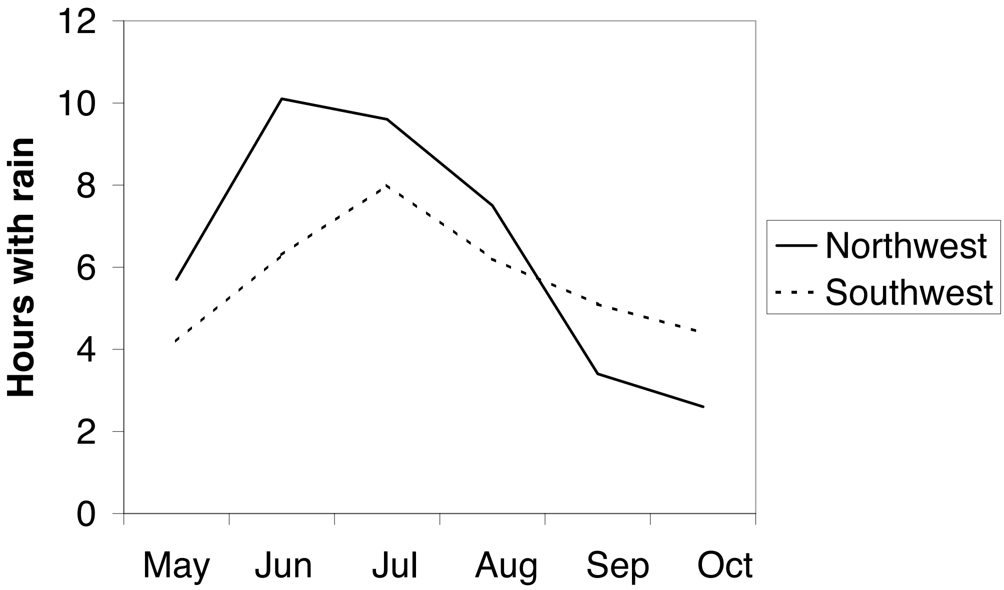


Figure 8 Mean number of hours with rain when wind was from "Southwest" (W, WSW, SW, SSW, S) or "Northwest" (NNE, N, NNW, NW, WNW), expressed as percentages of mean annual hours with rain. Perth, 1940-61 (after Wright, 1974a).

The early winter rainfall is sometimes associated with 'northwest cloudbands', extensive bands extending from off the northwest coast, through into mid-latitudes. In the southwest these sometimes interact with approaching cold fronts associated with mid-latitude synoptic depressions and form pre-frontal rainbands, contributing significantly to the total rainfall that may be associated with a frontal passage. It is this type of interaction that often gives widespread opening rains over inland agricultural and pastoral regions in late autumn or early winter. Wright (1997) and Telcik and Pattiaratchi (2001) note that, on average, 20-25% of the southwest's April-October rainfall is associated with interactions with northwest cloudbands. Most of this occurs in the early months of the season; cloudbands are rarer later in the season. Clearly, enhanced Type 1 rains are likely often associated with such interactions.

The concentration of the rainfall decrease in May-July (Figure 3 ~ refer page 2), the time of year when rainfall is most often associated with winds from the northwest and 'northwest cloudbands', suggests that the decrease in rainfall may have been associated with a decrease in the frequency, intensity, or preferred track of these cloudbands, or their interactions with cold fronts and mid-latitude depressions. This possibility, and its implications, is discussed in more detail later.

Causes of climate variations in the southwest – how important is the Southern Oscillation?

Despite Curlewis's optimism, droughts and floods do occur in the southwest. In winter these are related to variations in the atmospheric circulation. Perth mean sea level pressure (MSLP) provides a very simple index of the atmospheric circulation. Rainfall variations from year-to-year are closely related to variations in Perth MSLP (Allan and Haylock, 1993; Smith et al., 2000). If MSLP increases, then rainfall usually decreases (Figure 9).

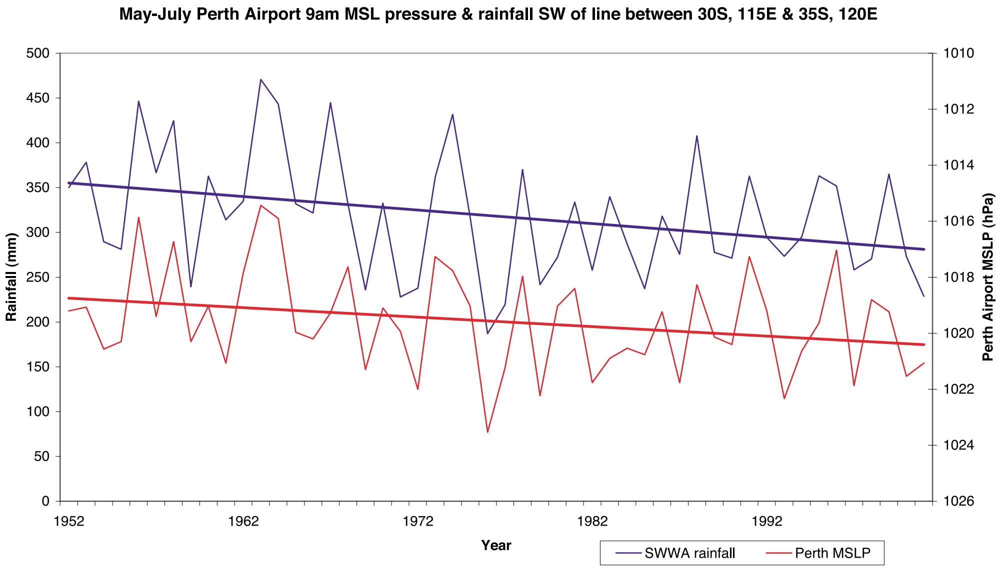


Figure 9 May-July Perth Airport 9am MSL pressure & rainfall SW of line between 30S, 115E & 35S, 120E. Note inverted scale for pressure time-series.

Figure 10 ~ refer next page ~ shows the correlation of southwest May-July rainfall with surface atmospheric pressure across the Australian region. Not surprisingly, given the relationship evident in Figure 9, years of high rainfall are accompanied by low pressures over most of the Australian region, with the strongest correlations (exceeding -0.8) over the southwest. Note also that the rainfall decrease was associated with an increase in atmospheric pressure (note reversed scale in Figure 9), suggesting that the rainfall decrease was at least partly the result of changes in atmospheric circulation measured by Perth pressure.

Atmospheric pressures across the Australian region are related to the El Niño – Southern Oscillation, so it not surprising the El Niño – Southern Oscillation is also related to climate in the southwest (Wright, 1974b). Air temperature in the southwest is also related to the El Niño – Southern Oscillation (Jones and Trewin, 2000).

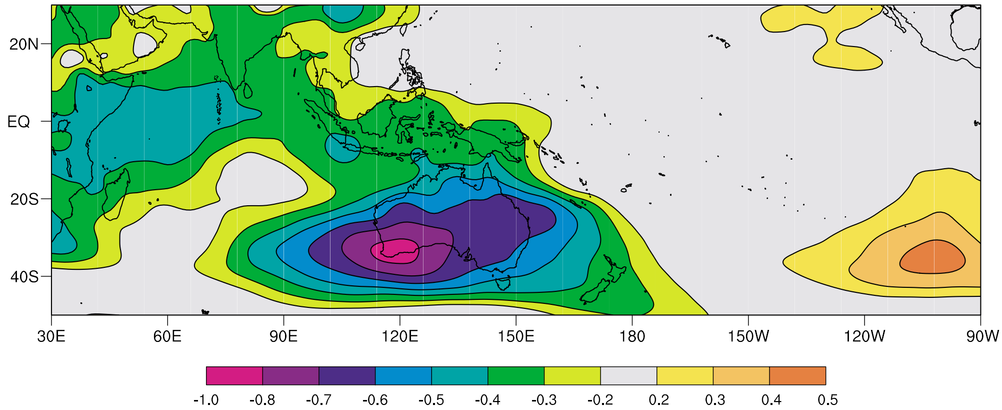


Figure 10 May-July rainfall correlated with sea level pressure from NCEP/NCAR reanalyses (1958-2001).

Since it is related to the climate of the southwest, can the El Niño – Southern Oscillation explain the observed decrease in rainfall? The Southern Oscillation Index (SOI, the standardized pressure difference between Tahiti and Darwin) is a commonly-used index of the El Niño – Southern Oscillation. When the SOI is strongly negative, rainfall over much of Australia is generally lower than normal. This includes the southwest (Figure 11). This figure shows, as well as the relationship between year-to-year changes in the SOI and rainfall (correlation = 0.34), that the decrease in rainfall after the mid-1970s was associated with a change in the SOI. This suggests that at least part of the rainfall decrease may reflect large-scale changes in the El Niño – Southern Oscillation.

> The climate of Perth (and, more or less, that of the whole south-western quarter of the State) is, in fact, the climate of the Mediterranean, of California, the Cape Province and Central Chile, all of which are characterized by mild, wet winters, warm dry summers, and a minimum of variation from year to year. Although neither drought nor flood are entirely unknown, they are extremely rare visitors to this part of Western Australia.
>
> E. B. Curlewis, "The climate of Western Australia", in H. A. Hunt, *Results of rainfall observations made in Western Australia*, Government Printer, Melbourne, 1929.

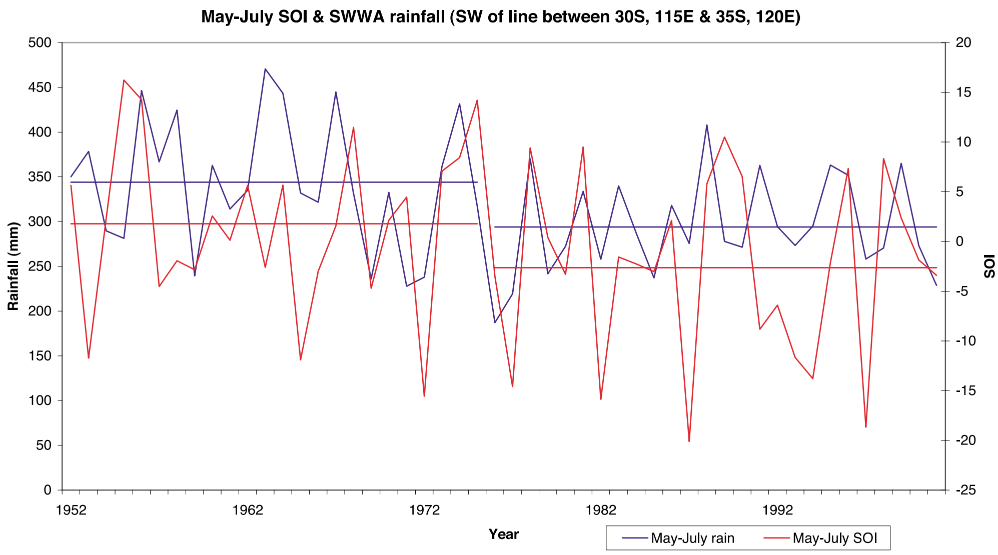


Figure 11 May-July SOI & SWWA rainfall (SW of line between 30S, 115E & 35S, 120E).

However, the relationship between Australian rainfall and the El Niño – Southern Oscillation has changed on multidecadal time-scales (Nicholls et al., 1996). In particular, the relationship with southwest rainfall in recent decades changed in the mid-1950s (Nicholls et al., 1999). The rainfall is now lower for any value of the SOI than was the case in the past. The cause of this change in the relationship is not known, but it does suggest that other factors may have been involved in causing the decrease in rainfall, rather than it simply reflecting a change in the character of the El Niño – Southern Oscillation. If it was simply the result of a change in the El Niño – Southern Oscillation, the relationship between the SOI and southwest rainfall would presumably have remained rather constant through the decades.

The El Niño – Southern Oscillation is related to sea surface temperature variations across much of the Indian and Pacific Oceans. But the largest ocean variations associated with the phenomenon are in the central and eastern equatorial Pacific, a long way from the southwest of Western Australia. Are floods and droughts in the southwest of Western Australia better related to Indian Ocean temperatures, rather than the equatorial Pacific temperatures generally associated with El Niño – Southern Oscillation? Figure 12 shows the correlation between rainfall in the southwest and sea surface temperatures in the Indian Ocean, during May-July. Sea surface temperatures across much of the southern Indian Ocean appear to be correlated with southwest rainfall, with warm temperatures usually being associated with dry conditions (Smith et al., 2000).

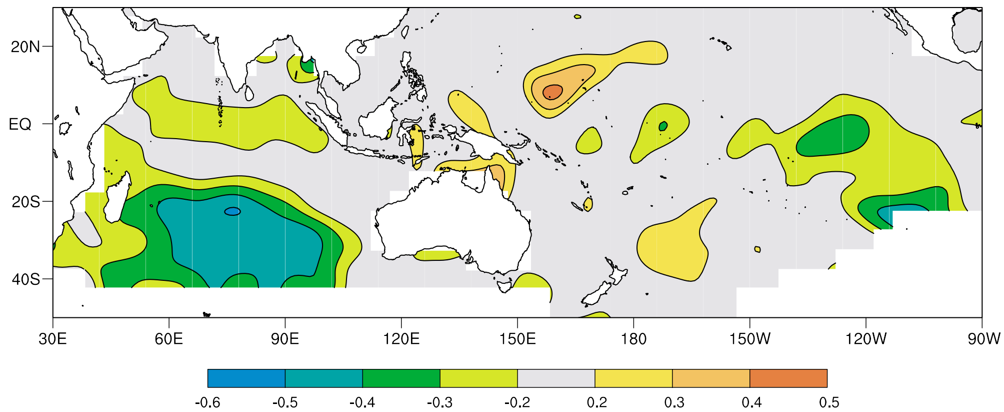


Figure 12 Correlation between southwest May-July rainfall and May-July sea surface temperatures (1952-2001).

However, most of this relationship reflects the fact that the Indian Ocean has warmed through the last few decades, as the southwest rainfall has decreased. Figure 13 shows the same correlation, but after year-to-year changes were calculated for the two variables.

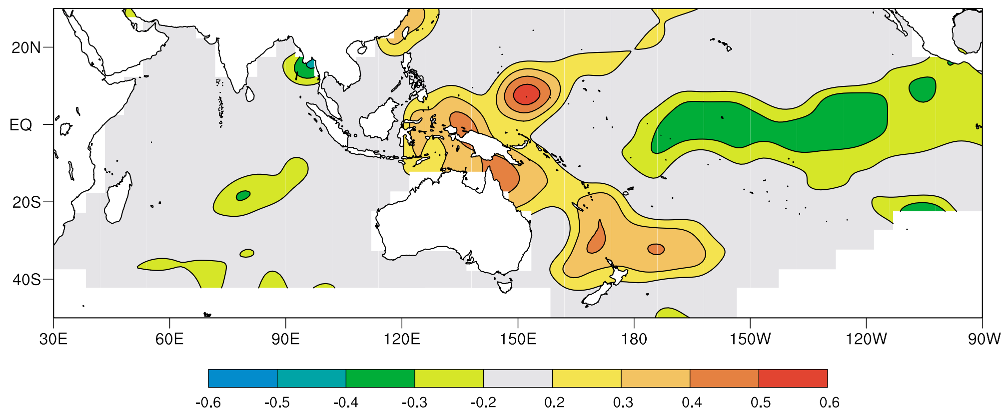


Figure 13 Correlation between year-to-year changes in May-July rainfall and sea surface temperatures (1952-2001).

The correlation with Indian Ocean temperatures has weakened. This suggests that the apparent link with the Indian Ocean simply reflects the fact that both variables have exhibited large trends in recent decades, rather than suggesting any real, physical and causal link between these trends. Smith et al. (2000) also found that the links between southwest rainfall and Indian Ocean sea surface temperatures were not robust, i.e., the correlations were not consistent across time, nor across seasons. However, the data from the Indian Ocean are sparse and inconsistent, and the analysis described above has used only simple linear statistical techniques. It may be that a more pervasive influence of the Indian Ocean could be detected as we develop more consistent Indian Ocean data sets and develop improved analysis techniques.

The Great Flood in Perth: "The flood which has just occurred during the last few days in Western Australia is unprecedented in the history of the colony. Some early settlers asserted that the flood of 1830 was as high if not higher than the present one, but there seems to be no data that we are aware of upon which to base this assertion. The amount of damage done during the present inundation must far exceed anything of the kind previously recorded, and heavy losses occurred in both life and property."

Extract from *Perth Gazette*, 11 July, 1862.

Figure 13 shows that, although there is little evidence that Indian Ocean sea surface temperatures are affecting the year-to-year variability in southwestern rainfall, there is however, a strong relationship with temperatures around Indonesia and northern Australia. This region is closely tied to the El Niño – Southern Oscillation.

What has caused the late 20th century decrease in rainfall – the enhanced greenhouse effect or natural variability?

Winter rainfall through the southwest has decreased to about 85-90% of the average observed in the middle decades of the 20th century (Figure 2 ~ refer page 2). The rather sudden drop in May-July rainfall in the mid-late 1970s was accompanied by a similarly sudden increase in atmospheric pressure (Figure 9 ~ refer page 12) and a drop in the SOI (Figure 11 ~ refer page 13). This suggests that large-scale processes, represented by changes in atmospheric pressures at Perth, were the proximate cause of the decrease in May-July rainfall. The number and intensity of synoptic depressions affecting the southwest have declined over the past 40 years (Simmonds and Keay, 2000). So the decrease in rainfall could reflect a decline in the mid-latitude events affecting the region. This would have reduced the chances of interactions with northwest cloudbands, possibly enhancing the rainfall decrease.

The increase in pressure at Perth and the change in the SOI were part of a major change in the atmospheric circulation that took place in the mid-1970s (Allan and Haylock, 1993; Smith et al., 2000). Figure 14a shows the most important pattern of variability in global atmospheric pressure. Tropical and subtropical regions from Africa across the Indian Ocean to the west Pacific tend to vary together, with 'out-of-phase' relationships with the northeast and southeast Pacific. Rainfall in the southwest is strongly correlated with this large-scale pressure pattern (Figure 14b). The time series in the bottom panel of Figure 14a shows that the intensity of this pattern jumped suddenly in the mid-late 1970s, at the same time that Perth pressure and the SOI jumped and southwest rainfall decreased (Figures 9 and 11 ~ refer pages 12 and 13). This sudden, large-scale change in the atmospheric circulation of the Indian Ocean sector can, then, be regarded as a partial 'cause' of the decrease in rainfall in the southwest.

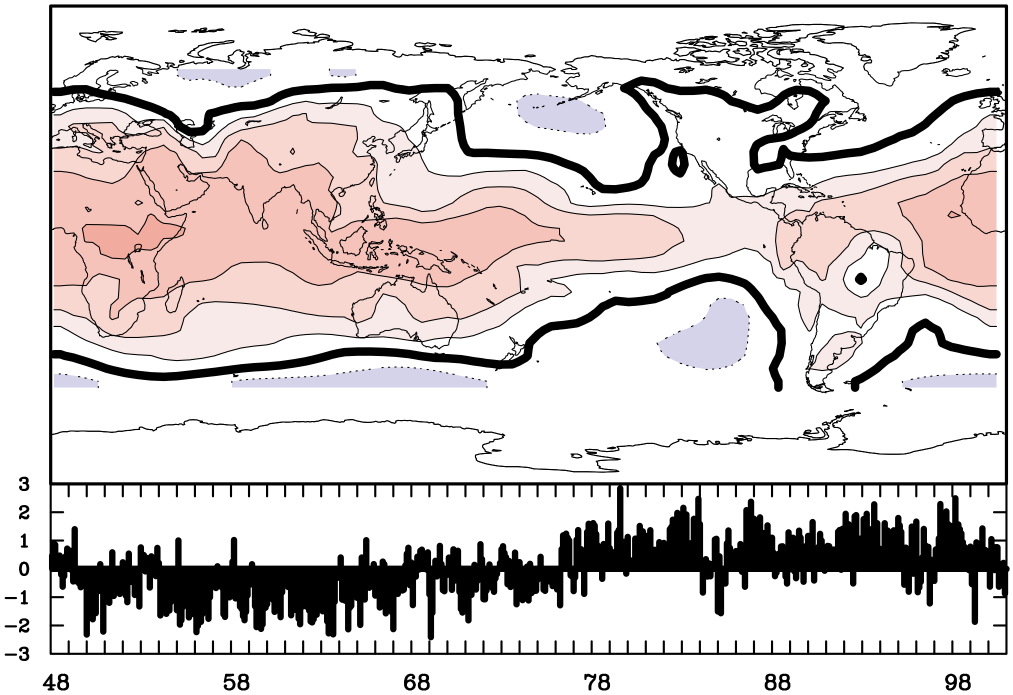


Figure 14a First principal component of global sea level pressure (top panel), and time-series of monthly strength of this component (bottom panel). Data from NCEP/NCAR reanalyses. The first principal component explains 15.1% of the total variance of the global sea level pressure field.

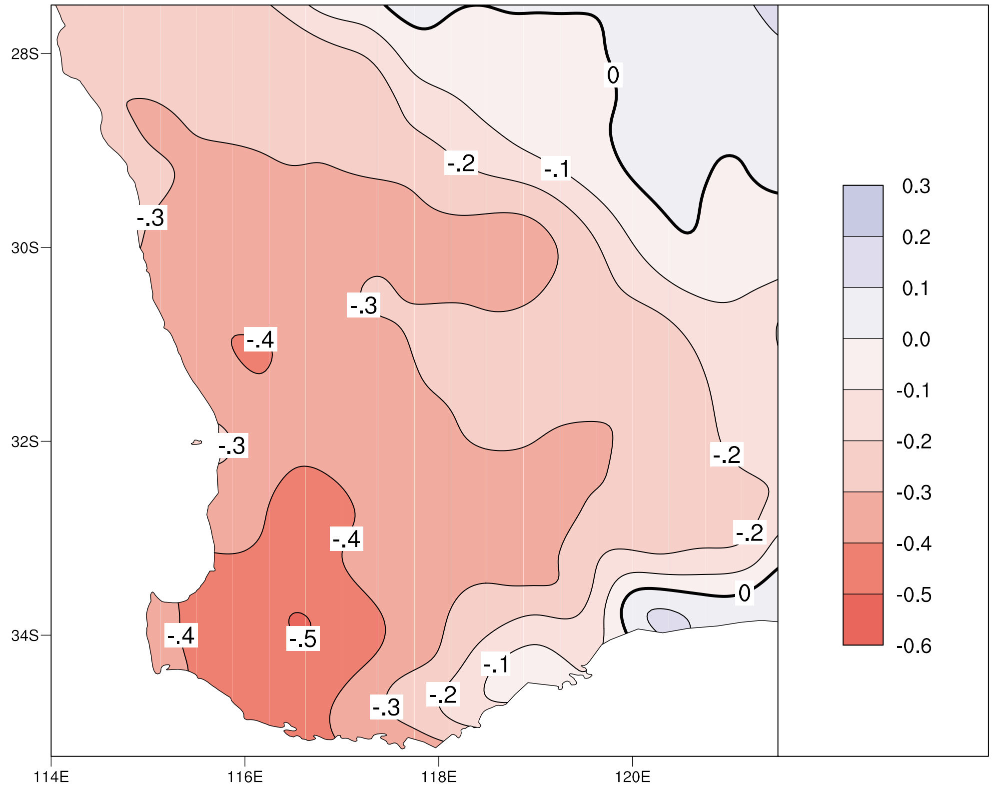


Figure 14b Correlation between May-July rainfall and strength of first principal component of global sea level pressure (from Figure 14a).

The decrease in rainfall was associated with changes in synoptic patterns over the southwest. Bates et al. (2000) identified six rainfall 'States' in the southwest, and related these to atmospheric data. Two important states were State 3, which produces widespread rainfall across the region but concentrated on the west coast, and State 5 with dry conditions everywhere. Figure 15 below shows the rainfall associated with these two States, plus the composite sea level pressure maps associated with them. State 3 occurs in association with a trough in the westerlies, whereas State 5 is dominated by a large anticyclone over southern Western Australia.

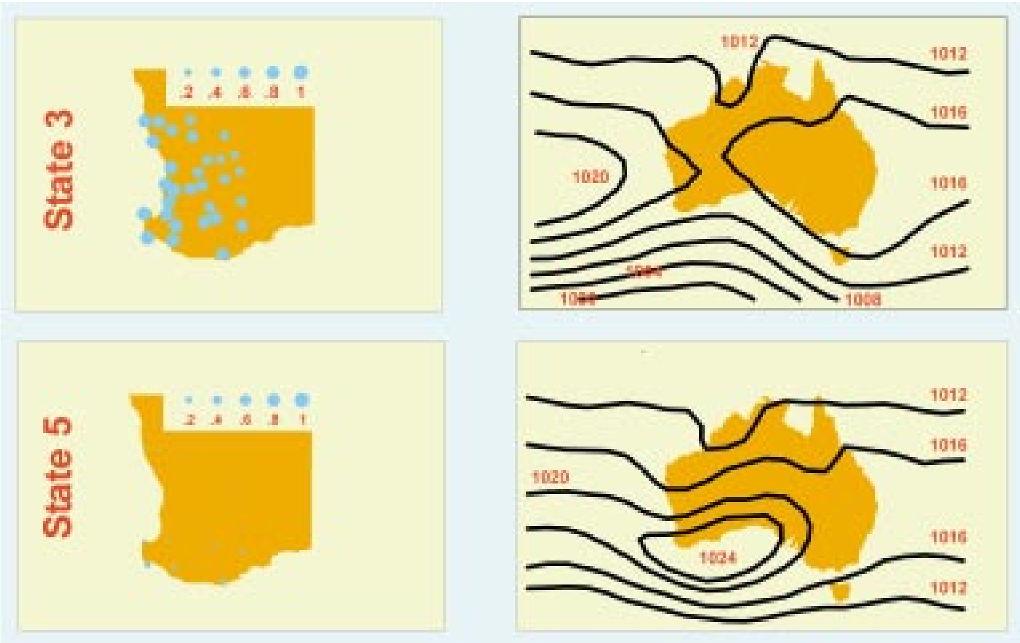


Figure 15 Atmospheric States 3 & 5. Left panels show rainfall associated with State - larger circles indicate intensity of rainfall; right panels show composite pattern of mean sea level pressures for the two States.

Figure 16 shows time-series of the frequency of each of these States. Since 1958 the 'dry' State (5) has increased in frequency, while the frequency of the 'wet' State (3) has decreased. Again, the changes in the frequency of these weather 'States' occurred rapidly during the mid-1970s, associated with the rapid, large-scale change illustrated in Figure 14a ~ refer previous page. The decrease in probability of State 3 is the result of a decrease in the moisture content of the lower atmosphere and the sudden increase in mean atmospheric pressure noted above.

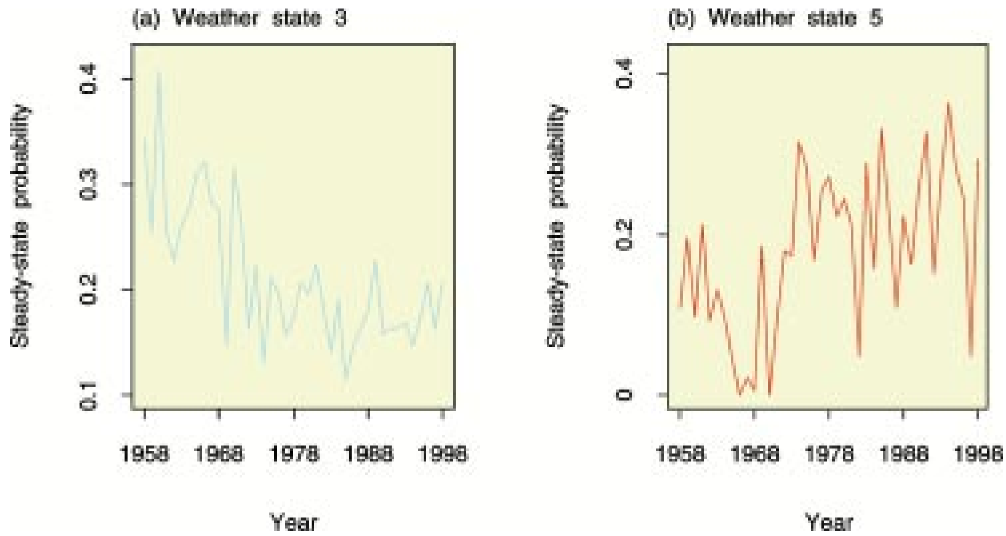


Figure 16 Time series of frequency of atmospheric States 3 & 5.

These changes in the frequency of weather 'States' suggest a change in the frequency or intensity of cold fronts affecting the southwest. The observed decrease in the number and intensity of mid-latitude depressions affecting the southwest (Simmonds and Keay, 2000) supports this hypothesis. There has possibly been an additional effect in that weaker or less frequent cold fronts would have less opportunity to interact with cloudbands, which themselves may have adopted more northerly tracks. This is suggested by the trend of increasing rainfall over the southern pastoral regions (Figure 2 ~ refer page 2). Less frequent or weaker cloudband interactions would have a particular impact on the frequency of heavy daily rainfall events.

A consistent satellite data base stretching back well before the mid-1970s, which unfortunately does not exist, might provide more direct evidence as to whether the rainfall decrease was associated with a change in the frequency or intensity of these cloudbands and their interactions with cold fronts and mid-latitude depressions. However, the association of this decrease with the changes in the frequency of atmospheric synoptic States (Figure 16 above), and with large-scale atmospheric pressure changes lends support to this argument. The fact that the large decrease has occurred at the time of year when interactions between cloudbands and cold fronts are an important rain-bearing mechanism adds credence to this hypothesis.

What is the underlying cause of these changes in rainfall? The suggestion (Gentilli, 1971) that the recent decline in rainfall is returning southwest rainfall to levels observed at the end of the 19th century (after a relatively wet early 20th century), might mean that the recent decrease could be the result of natural variability of the climate. But we also need to consider other possible causes.The IPCC concluded, in its Third Assesssment Report, that "There is new and stronger evidence that most of the [global] warming observed over the last 50 years is attributable to human activities" (Houghton et al., 2001).

It is reasonable, therefore, to attempt to determine whether the changes observed in the southwest might be a consequence of the enhanced greenhouse effect or other human influences. Climate models from various international research institutes including CSIRO have been run with an enhanced greenhouse gas content (Figure 17). Most of these simulations suggest that rainfall in the southwest might decline with an enhanced greenhouse content, although there are considerable variations between the models' predictions of the magnitude of this expected decline. Although climate models are not considered particularly reliable on the spatial scales of the southwest, the available evidence does suggest that the enhanced greenhouse effect may have contributed to the recent rainfall decline.

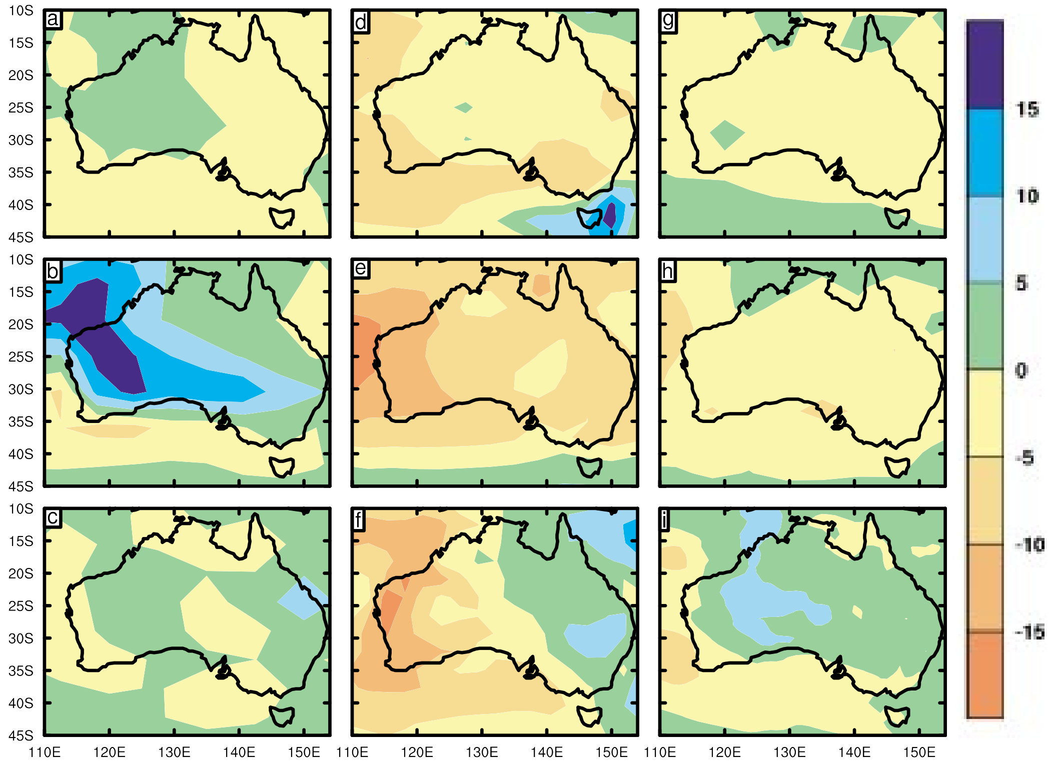


Figure 17 Percentage change (per degree change in global surface temperature) in Australian rainfall in various models run with enhanced greenhouse gas concentrations.

As an example of these simulations with enhanced greenhouse gas concentration, Figure 18 ~ refer next page ~ compares winter (June-August) rainfall at Manjimup with the results from a CSIRO 'Mk3 model' transient climate experiment. The transient run is a simulation with increasing effective carbon dioxide and increasing aerosol content beginning in 1960. Effective carbon dioxide in the model doubles by 2065. The model results are from averaging across a grid box approximately 200km x 200km covering Perth and surrounds. The model simulation indicates a downward trend of rainfall in the Perth area of about 20% over 100 years, comparable to, but weaker than, the observed decrease.

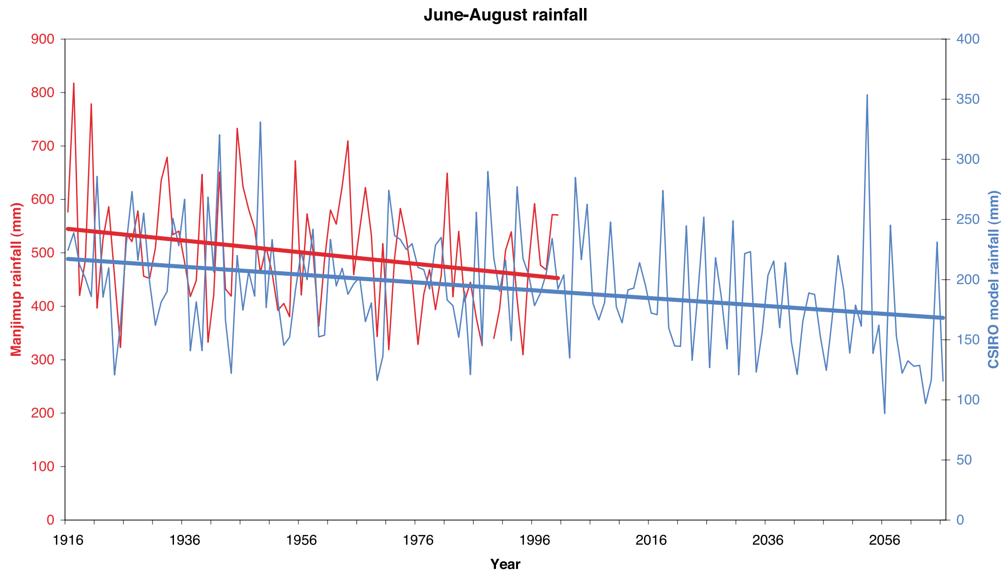


Figure 18 June-August rainfall at Manjimup (in red). CSIRO model rainfall for a grid box surrounding the Perth area (in blue), when model is run with increasing greenhouse gases from 1960.

As was noted earlier, the decrease in rainfall has been associated with major changes in the large-scale atmospheric circulation in the Indian Ocean region. In order for the enhanced greenhouse effect to be considered a likely cause of the observed rainfall decrease, it would be necessary to demonstrate that the models produce a similar change in large-scale atmospheric pressure when they simulate the enhanced greenhouse effect. Figure 19 shows the simulated change in atmospheric pressure in the transient run of the CSIRO model. It suggests a strong increase in pressure between 30 and 50S around the hemisphere as the proximate 'cause' of the decline in rainfall found in the model. The model results suggest that the enhanced greenhouse effect might lead to an increase in atmospheric pressure in the latitudes of the southwest.

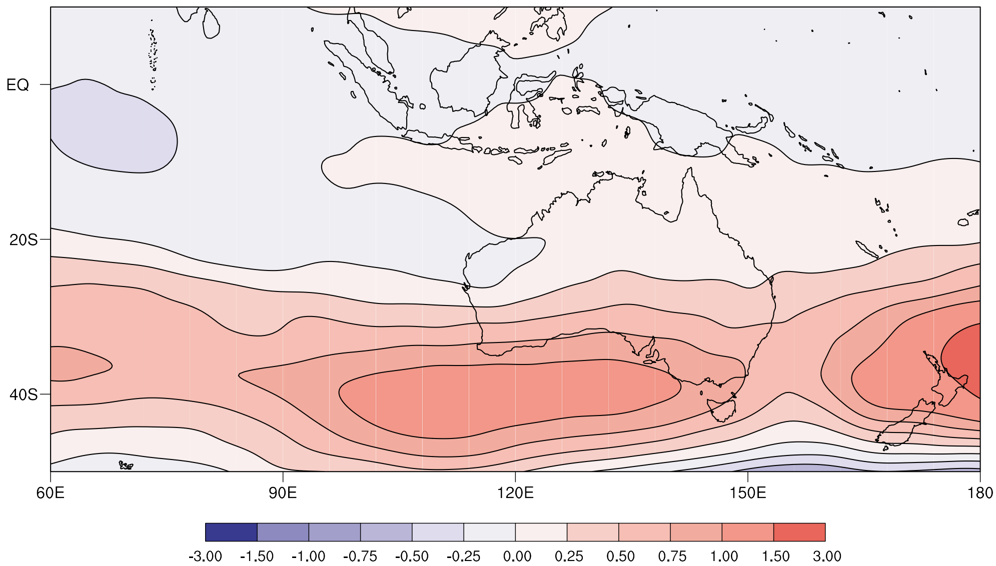


Figure 19 Change in June-August surface atmospheric pressure, from the period 1986-2015 to 2036-2060. Data from CSIRO model with increasing greenhouse gases.

Figure 20 shows the observed change in sea level pressure in the Australian region from 1958-1975 to 1976-2001. This figure has some similarities to the model change in sea level pressure in the transient run, with the largest changes in pressure around the southern edge of the continent. This suggests that at least some of the observed decrease in rainfall, since it is related to this increase in atmospheric pressure, may be due to the enhanced greenhouse effect. However, the observed pattern of change in pressure is not identical with that in the model simulation. Importantly, the model predicts decreases in tropical pressure, whereas pressure in these regions has actually increased (Figure 20). Thus the explanation for the increase in pressure and decrease in rainfall may not simply and solely be the enhanced greenhouse effect.

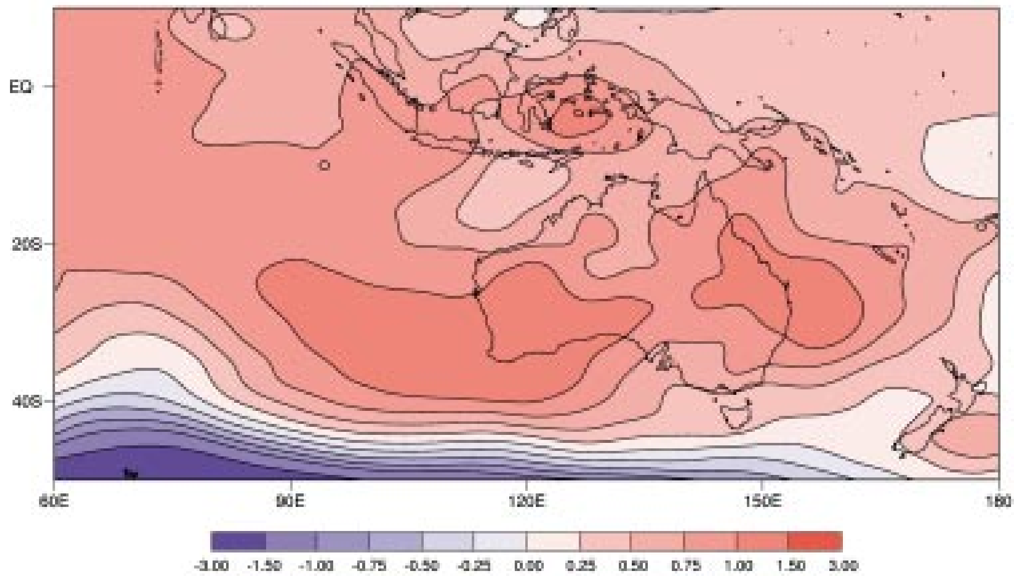


Figure 20 Change in June-August sea level pressure (from NCEP/NCAR reanalyses) from 1958-1975 to 1976-2001.

Other factors such as land-use changes (either local or global), air pollution (again local or global), and changes in solar forcing, may have contributed to the decrease. Some recent model simulations do suggest that large-scale changes in rainfall may be caused by large-scale forest removal. Some recent studies (e.g., Ray et al., 2002) have found that in the southwest cumulus cloud frequency is different over native vegetation areas than over agricultural land. However, it is still not obvious that this effect could have contributed to the observed decrease in winter rainfall. Narisma and Pitman (2002) found that southwestern Australia winter rainfall decreased in their climate model if they replaced original (1788) vegetation over Australia with modern vegetation type and cover. However, the decline was much weaker than that observed, suggesting that the local land use change was at best a secondary cause of the rainfall decrease. One argument against a major role of local land-use changes is that there are strong rainfall decreases towards the coast and even off the coast at Rottnest Island (Figure 4 ~ refer page 3), where land-use changes have been smaller than further inland. It is difficult to see how changes in land-use further inland could lead to these rainfall decreases. Another argument is that the observed rainfall decrease has been associated with the change in the large-scale pattern of climate variability (Figure 14 ~ refer page 16). The chances of a local factor such as land-use changes or local air pollution sources causing a large-scale change of this scale are low. It may however be that at least part of the shift illustrated in Figure 14 ~ refer page 16, and the accompanying rainfall decrease in the southwest, are both just part of the natural variability. Further model experiments are required to confirm or deny this.

At the moment, on the balance of probabilities, our best estimate is that both natural variability and the enhanced greenhouse effect may have contributed to the observed decrease in rainfall in the southwest. It is impossible to estimate, yet, the contribution of each factor to the decrease. Other possible contributing factors (e.g., land use change) are yet to be tested fully, and further work is required to determine the relative influences of all factors. These local factors, however, seem likely to have only been second-order contributors to the rainfall decrease.

The increased temperatures, on the other hand, seem most likely to be attributable to the enhanced greenhouse effect, since such increases have been near-global, and are predicted by climate models with enhanced greenhouse gases.

Predicting seasonal climate variations in the southwest – can we improve on the Southern Oscillation?

"The records of past seasons, for instance, are, I consider, indispensable to the success of most of the inexperienced men on the land. By a study of his district's seasons in the past, a young settler is able to avoid under or over expenditure in increasing stock or in improvements. The records will tell him how many good, bad, or indifferent years he is entitled to expect; and he will not be over optimistic after a good season nor over pessimistic after a bad one."

H. A. Hunt, *Results of rainfall observations made in Western Australia*, Government Printer, Melbourne, 1929.

What are the prospects for useful seasonal prediction in this region? Current operational forecasts issued by the Bureau of Meteorology use near-global sea surface temperature (SST) patterns to predict seasonal rainfall and temperature in the coming season. This section looks at the skill of this system in the south-west of Western Australia as well as the possibility of using other climate predictors, such as the Southern Oscillation Index (SOI), the Antarctic Circumpolar Wave (ACW), indices of the so-called Indian Ocean Dipole (IOD) and mean sea level pressure (MSLP).

The possibility of making forecasts for total cool-season rainfall (May to October) and spring (September to November) and summer (December to February) rainfall and temperature was investigated. These seasons and variables were selected after discussions with industry representatives, especially from the agriculture and water sectors. The temperature forecasts investigated were for mean temperature, mean maximum temperature and mean minimum temperature. Area-averaged temperature and rainfall data were used for regional forecasts and data from six individual stations (Figure 1 ~ refer page 1) used to assess regional variations. Probability forecasts were prepared, either expressing the probability of rainfall (or temperature) either being above (or below) the median or of falling within each of three categories or 'terciles' (below average, near average, above average). The lead times for the various forecast 'targets' varied, but were usually a month or two ahead, to allow some opportunity for decisions to be taken based on the forecasts. For instance, May-October rainfall forecasts used predictors from April and February.

Test forecasts were made using data from 1949 to 1998. The skill of the forecasts was measured with accuracy or 'hit' rates. This is the ratio of the number of 'consistent' forecasts (i.e. when the category observed is the one that was forecast to be most probable) to the total number of the forecasts, expressed as a percentage. If there were no skill in the forecast system, we would expect an accuracy rate of 50% for two-category forecasts (i.e. below or above the median), the same as achieved simply by guessing.

A brief description follows of the predictors assessed in this study. The sea surface temperature (SST) patterns used were the most important patterns of variation of Pacific-Indian Ocean SSTs (Drosdowsky and Chambers, 2001). The first pattern, SST1, is closely related to the El Niño – Southern Oscillation. The second pattern, SST2, represents variability in Indian Ocean SSTs. The Southern Oscillation Index (SOI) is the normalised air pressure difference between Tahiti and Darwin. This index is strongly correlated with SST1. The Antarctic Circumpolar Wave (ACW) variables were derived from an analysis of the Southern Ocean SSTs. White and Peterson (1996), White and Cherry (1999) and White (2000) describe the ACW, which appears to have an eight-year periodicity, propagating eastward at an average speed of 45 degrees of longitude per year. The Indian Ocean Dipole (IOD) was proposed by Saji et al. (1999) and Webster et al. (1999) who suggest that the dynamics of the equatorial Indian Ocean leads to a dipole structure in SSTs which could affect the climate of the surrounding region. The mean sea level pressure (MSLP) indices are the most important patterns of variation in pressure data between 55ºS and 65ºN. The first pattern, MSLP1, is centred over the western Pacific Ocean and covers most of the tropics and subtropics, except for the eastern Pacific. The second pattern, MSLP2, covers the central and eastern Pacific and western coast of southern America.

The current operational forecast scheme, using SST1 & 2, generally performed as well as, if not better than, most of the other predictors tested. The median accuracy (hit) rate for all the operational-scheme forecasts was 59%. MSLP1 & 2 also performed well (median accuracy rate also 59%), particularly for May-October rainfall (median 60%) and spring temperature forecasts (median 65%). In general, the use of the IOD variables did not lead to very skilful forecasts (medians of 50-54%, depending on which IOD variable was used).

The highest skill levels were achieved for spring temperatures, particularly mean and mean minimum temperatures (median accuracy rates of 63% and 67% respectively). The lowest levels of skill were for summer mean and mean maximum temperatures (medians of 51% and 41% respectively). Most accuracy rates for rainfall were close to 50%, indicating at best only limited levels of skill.

These results were for forecasts of the area-averages. In general these area-averaged forecasts represented the region quite well, but there was some variation in skill between these and the forecasts for the six individual stations. For winter rainfall forecasts the area-averaged results indicated a higher level of skill than was obtained at the individual station level, though the level of skill was only moderate. The median accuracy rate for the area-averages was 59%, while those for the individual stations ranged from 41% to 58%. For summer mean maximum temperature forecasts, however, the area-averaged skill (median accuracy rate of only 41%) was considerably lower than for many of the individual stations, e.g. Jarrahdale (57%) and Lake Grace (61%). Otherwise the results for the area-averaged results were similar to those of most of the individual stations.

Rainfall, particularly in winter, proved difficult to forecast at most stations, while spring temperatures exhibited generally higher skill levels. Rainfall and temperature predictions for Jarrahdale, Merredin and, to some extent, Manjimup and Lake Grace, appear to be promising while there appears to be some difficulty in providing skilful rainfall and temperature forecasts for locations such as Kalgoorlie and, to some extent, Mingenew. These spatial and temporal variations of the forecasts are consistent with the results of Drosdowsky and Chambers (1998) and Jones (1998). Some of the difficulty in predicting rainfall for winter lies in the problem of predicting the behaviour of the El Niño – Southern Oscillation across autumn. This is a problem with seasonal climate prediction wherever the El Niño – Southern Oscillation phenomenon affects climate, not just the southwest. Another factor contributing to the rather low skill is that the relationship between the El Niño – Southern Oscillation and southwest rainfall has changed over time.

How accurate are these forecasts, relative to other areas and seasons where seasonal forecasts are accepted as showing potentially useful skill? Forecasts for spring rainfall in Queensland and northern New South Wales exhibited greater skill than do the spring rainfall forecasts for the southwest, however, the skill of such forecasts in Victoria and South Australia was about equal to that in the southwest. The reality is that almost anywhere in Australia, at best only moderate levels of skill are obtainable in seasonal climate prediction. The southwest seems little different in this respect.

All the work described above uses 'linear' statistical approaches. Linear techniques assume, for example, that changes in sea surface temperature influence rainfall in a continuous, smooth fashion. There is however evidence that the climate system can behave in strikingly non-linear ways. For example, Graham and Barnett (1987) show that in the tropics enhanced convection occurs at sea surface temperatures greater than about 29ºC. This implies that different rainfall forecasting systems should be used in the tropics, depending on whether sea surface temperature is above or below the threshold temperature of 29ºC.

IOCI has developed an approach to non-linear forecasting, which is still very new and at the frontier of climate science. A graphical check for non-linear behaviour has been developed, with the 'switching' variable being sea surface temperature gradients in the mid-Indian Ocean. This suggests that a threshold does exist, implying that non-linear forecasts may improve on linear approaches. Different linear forecast equations apply in the two regimes – below and above the threshold. Thus the onset of winter rains at Rottnest Island can be forecast by monitoring sea surface temperature gradients in the mid-Indian Ocean (IOCI, 2001). Further work is needed to assess how much extra skill is possible using non-linear approaches, and to investigate its use elsewhere in the region.

Other IOCI research is investigating the use of a global coupled atmosphere-ocean model to generate forecasts of the atmospheric predictors required for Weather State prediction (such as the States in Figure 15 ~ refer page 17). The coupled model is started from observed sea surface temperatures and surface wind stress and then run to produce forecasts up to 12 months in advance. The aim is to produce a probabilistic forecast of winter rainfall with a lead-time of 2-6 months. Initial testing of this approach has been encouraging.

Using our knowledge of seasonal climate variability of the southwest – towards better operational decisions

The climate variations in the southwest have a marked impact on the economy and environment. One example of this is illustrated in Figure 21 below, which shows correlations of monthly climate variables with the annual wheat yield for Western Australia. The climate variables have been averaged across the Western Australian wheat belt, which lies largely north and east of the defined study (southwest) region. Generally, higher than normal daytime temperatures, or lower than normal rainfall and/or night-time temperatures, lead to decreased yields. So, being able to predict, well in advance, the rainfall and temperature of the southwest could lead to the ability to predict wheat yields, well before harvest.

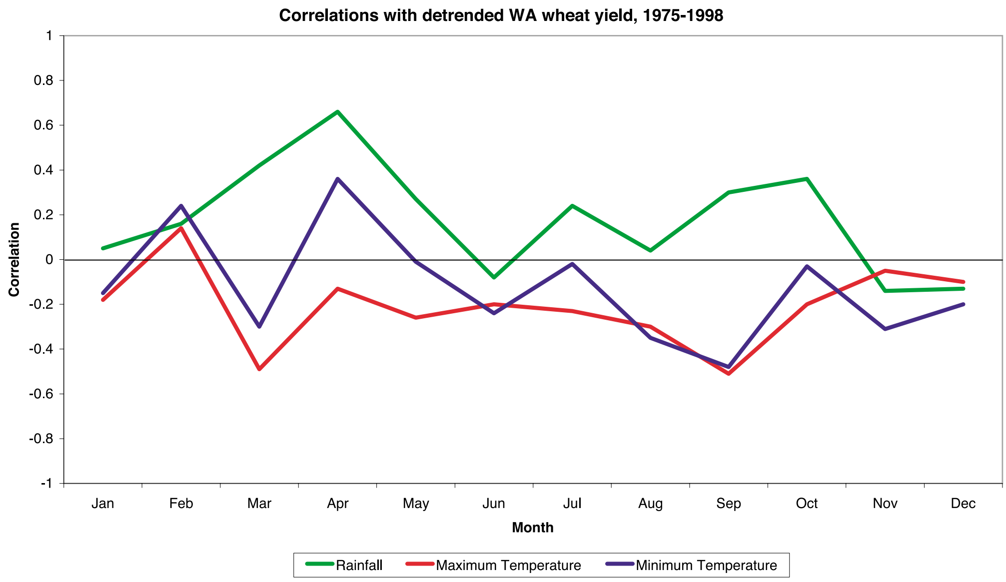


Figure 21 Correlations between monthly rainfall totals, monthly mean maximum and minimum temperatures (all averaged across the Western Australian wheat region), with annual detrended mean Western Australian wheat yields. Data from 1975-1998.

Such forecasts would be useful for crop marketing and transport, and perhaps also for economic, state-wide, forecasting. But would skilful seasonal forecasts, if these were available, be useful in agricultural, on-farm decision making in the southwest? There are two types of decisions facing producers every year, strategic and tactical. Strategic decisions are major, concern the overall farm plan, and are usually made over the summer period. They must be resolved before the winter season begins, and are likely to benefit from skilful seasonal forecasts, if such forecasts are available sufficiently early (i.e., during summer). Tactical decisions arise once the season has begun, and are typically made in response to current seasonal conditions.

Some of the major strategic decisions are:

- Crop variety and rotation.
- Area devoted to crop or pasture.
- Amount of fertiliser.
- Amount of herbicides for weed control prior to crop establishment.
- Amount of fuel to be ordered.
- Types of machinery, especially for crop establishment.
- Marketing, forward selling, yield estimates.
- Animal husbandry issues – feed supply and quality, water supply.

Tactical decisions can include:

- Whether to top-dress with added fertiliser to take advantage of better growing conditions.
- Whether to spray for fungal diseases or insect attack.
- Whether to de-stock because of poor pasture growth or lack of water.
- Whether to re-seed because of poor crop emergence.

As well as the on-farm impact of these decisions, there are many dependent agribusinesses that are affected. For example, a late onset of winter will cause growers to change to shorter season crop varieties. This will mean a run on seed stocks of those varieties. An expectation of a wetter winter could mean that more crop will be planted, needing more fertiliser and fuel, meaning that suppliers would need to hold more stocks.

Agricultural commodity markets are keenly sensitive to seasonal variations and expectation, as well as to market manipulation. Changes in anticipated prices can have a feedback into decisions made by producers. For instance, higher wheat prices and poorer returns from wool in 1996 led to an increase in the area sown to wheat.

Seasonal forecasting also has the potential to influence long term land resource degradation through better matching of agricultural management and seasonal conditions. Lack of ground cover during dry winters is a major risk factor for wind erosion of soil. Reliable seasonal forecasts can greatly assist in early removal of stock and maintenance of adequate stubble cover.

However, as shown earlier, the skill of seasonal rainfall predictions, especially for winter rainfall, is moderate at best. So it seems that, at the moment, use of the currently-available seasonal forecasts is unlikely to help in making strategic decisions, such as the choice of crop variety. On the other hand, any tactical decisions affected by temperatures, especially those in spring or summer, may be assisted by the more skilful forecasts available for this variable and seasons.

Application: using observed climate to predict wheat yield.

Perhaps such forecasts are not even needed if we are to take advantage of what we know about the climate. The most intriguing aspect of Figure 21 ~ refer previous page ~ is that the strongest correlations are with climate variables about the time of planting, i.e., April. Thus April rainfall has a correlation of 0.66 with wheat yield. So, simply monitoring the climate variables around the time of planting can provide good predictions of wheat yield. This presumably represents a relationship between early ‘break’ rains and time of planting – good rains early in the season would lead to an early planting of the crop, leading generally to good yields. Of course, not all economic or environmental variables affected by climate would be predictable with such a simple system, on useful lead times.

Can other climate-dependent sectors use climate observations more intensively, to predict outcomes and outputs, as appears to be the case with agriculture? If so, the rather moderate skill obtainable from climate forecasts might not be a hindrance to improved use of climate information in the southwest.

Application: soil dryness index for managing bushfires.

The soil dryness index (SDI) is a numerical value reflecting the dryness of soils, deep forest litter, logs and living vegetation. Soil dryness is used to plan the timing of prescribed burning in spring and autumn in the southwest of Western Australia, and to plan the level of preparedness for wildfire emergencies. The timely availability of forecasts of SDI would be of significant benefit in planning these activities. IOCI is developing a forecasting system for SDI. A set of forecasts for SDI at Manjimup is shown in Figure 22. The first forecast is simply the average of the preceding 5 years, known as 'P5YWA'. The other two approaches, 'SD' and 'SARIMA', use the strong seasonal pattern of SDI to produce forecasts. SARIMA produces the most accurate forecasts overall, although none of these perform well when large rainfall events occur in summer. Future research will seek to improve the approach in this case because summer conditions are an important factor in mitigating bushfire impacts.

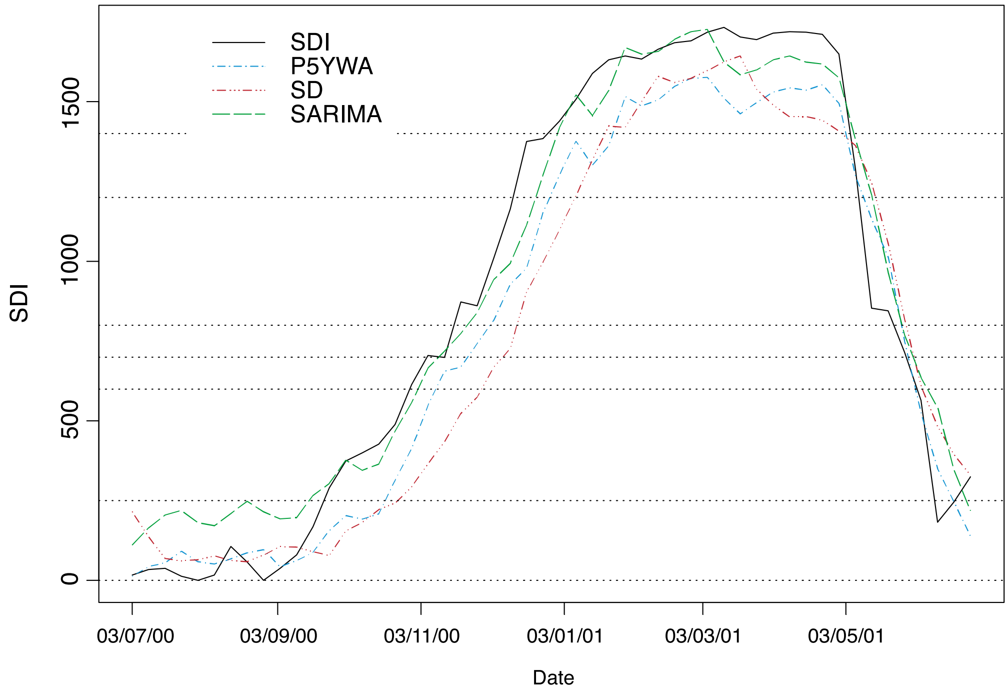


Figure 22 Observed (full line) and predicted Soil Dryness Index (SDI) for Manjimup for 2000/2001.

Projecting future climate change – Practical baselines for planning and adaptation to change

Rainfall

Our inability, at this stage, to conclusively identify the cause of the observed rainfall decrease in the southwest makes it difficult to decide climatological baselines for future planning in this region. Should we anticipate that rainfall levels will return to the higher levels of the mid-20th century? Should we assume that rainfall is likely to be centered about the lower levels of the late 20th century (which were similar to, although somewhat drier than, those around the start of that century)? Might conditions be worse because of the enhanced greenhouse effect?

Furthermore, because different risk-structures and decision time-frames will be associated with various industry sectors no single base-line approach is likely to maximise opportunities or minimise regrets for all circumstances of adaptive decision-making. Here we state what is understood about climate expectations but stop short of the decision judgements that must be tailored specifically for different decision environments.

If we were confident that the enhanced greenhouse effect had been the dominant factor in causing the decrease it would seem reasonable to anticipate a continuation of the recent low rainfall. Alternatively, if we could conclude that natural climate variability had been the main cause of this low rainfall, we might conclude that at some stage rainfall would increase. Since we have concluded that some combination of the enhanced greenhouse effect and natural climate variability appears the most credible explanation for the decrease, how do we proceed?

We would need to recognise that –

- Sustained dry runs, such as in the last quarter century, are a natural aspect of variability in this region, as are sustained wet runs typified by the middle half of last century, even if natural variability was the sole cause of climate variation.
- The natural climate of the 21st century would be expected to exhibit such, presently unpredictable, regime shifts as we have observed during the 20th century.
- The anticipated climate effects of enhanced greenhouse conditions, and possibly other human influences, needs to be overlaid on this natural variability.
- The general greenhouse scenario for this century is an expectation that temperatures will be warmer than in the last. Rainfall projections are more difficult and approximate. Most models, however, suggest a decline of autumn and winter rainfall in southern WA over coming decades, relative to what would be the case without an enhanced greenhouse effect.

How will natural variability and global climate change interact? One way to include both factors might be to attach similar likelihoods to the recurrence of extended runs of wet and dry years as in the last century, but to weight their expected means and ranges progressively drier as this century progresses.

A range of more specific planning scenarios would need to be considered around these general expectations according to the particular planning circumstances and risk structures. These should include consideration of alternative greenhouse gas emission scenarios recently published by the IPCC and interpreted nationally by CSIRO.

Temperature

For temperature, it seems reasonable to assume that temperatures would continue, in the main, to be higher than the historical climatological average, because of the presumed relationship between the enhanced greenhouse effect and warming in this region. The IPCC expects continued global warming through the 21st century, due to the enhanced greenhouse effect.

Combined Projections

The combination of these rainfall and temperature projections for the southwest could be used to forecast evapo-transpirative demand, and other climate-affected demands as well as climate-affected supply factors for water and other service, industrial and primary sectors. Even without changes in the rainfall of the southwest, the higher temperatures anticipated with an enhanced greenhouse effect should reduce run-off and increase demand for water by humans, animals, and vegetation.

There are also other potential changes associated with the enhanced greenhouse effect, such as changes in extreme rainfalls and wind velocities, that may need consideration, but projections for some of these are extremely uncertain and have not been investigated in any IOCI activity. Where information is needed on such matters, some discussion is available in recent IPCC and CSIRO reports.

Unanswered questions

Our inability to provide definitive answers to questions such as "What is the cause of the observed rainfall decrease" partly reflects the difficult nature of climate research, but also indicates that some work is yet to be completed that may assist in answering such questions. The major scientific challenge, if we are to provide more definitive projections of the climate of the southwest, is to determine the relative influences of natural variability and the enhanced greenhouse effect in causing the recent decrease in rainfall. IPCC projections of rainfall changes expected with the enhanced greenhouse effect are less confident than the projections of temperature change, even on a global scale. Rainfall is also likely to exhibit considerable regional variations in its reaction to the enhanced greenhouse effect, because of the often-complicated relationships between orography, large-scale atmospheric circulation, and rainfall. So more detailed model experiments, and also research to improve confidence in projections of rainfall change on the scale of the southwest are needed.

As well as improved projections of the likely impact of the enhanced greenhouse effect, we also need improved estimates of the natural variability of the southwest climate, so that we can determine how much of the recent dryness can be attributed to natural variability. Paleoclimatic research, to provide a longer period of record of the climate of the southwest, could assist in this. More detailed study of the synoptic meteorological events leading to rainfall, and the way these events have changed over the 20th century, could also shed light on the relative contribution of the greenhouse effect and natural variability to the recent drying. The recognition that changes in cold front and cloud-band frequency and impact on the region may have contributed to the rainfall decrease is a recent step forward. Work could be done investigating changes in cloud and synoptic system occurrence over the southwest around the mid-1970s. Such work may allow a more definitive determination of how much of the rainfall decrease was related to changes in these synoptic systems.

The possibility that high-latitude changes in the atmospheric circulation, caused by photochemical ozone losses (Thompson and Solomon, 2002) may also be contributing to the decrease in rainfall also needs to be considered. The increase in pressure south of Australia (Figure 20 ~ refer page 21) seems likely to be related to the recent changes in the high latitudes, which in turn seem to be related to the decline in ozone amount over Antarctica. The various factors that could account for the rainfall decrease (natural variability, greenhouse effect, ozone depletion) need to be assessed in more detail.

Research is also needed to determine whether other, more local or regional, factors could be contributing to the drying. For instance, model experiments could be undertaken to provide a better estimate of the possible impacts of local land-use changes on the region. The results of studies of the climate impact of global land-use changes could also be examined, to determine if these were likely to have contributed to the rainfall decrease. Climate model experiments might be considered to investigate the possible impacts of local sources of air pollution on the climate, even though these seem likely to be, at best, only secondary contributors to the decrease.

The investigation of climate variability on decadal time-scales, and the possibility of predicting variations on these time-scales is an important current research topic. More could be done to utilise this research in an attempt to understand the possibility that the rainfall decrease is just part of natural variability. Such research may also lead to improved forecasts of interannual variability in the southwest, since the large-scale changes in climate have created difficulties in using the El Niño – Southern Oscillation in short-range climate prediction.

A major factor limiting seasonal climate prediction, in the southwest and elsewhere, is the difficulty of forecasting the behaviour of the El Niño – Southern Oscillation around March-May. This period is crucial for many users of climate information in the southwest. An intensified effort to search for solutions to the prediction through this 'autumn predictability barrier' is needed.

Finally, further work could be undertaken to ensure that what predictability does exist, on either long time-scales or on the seasonal-to-interannual time scale, is used and useful to those living and working in the southwest. The appropriate use of climate forecasts requires more care, and more interaction between climate scientists and potential users, than is often realised. This is especially so when, as is the case with the southwest, the climate predictions are necessarily uncertain.

Acknowledgement

David Stephens provided the wheat yield data for Figure 21 ~ refer page 26.

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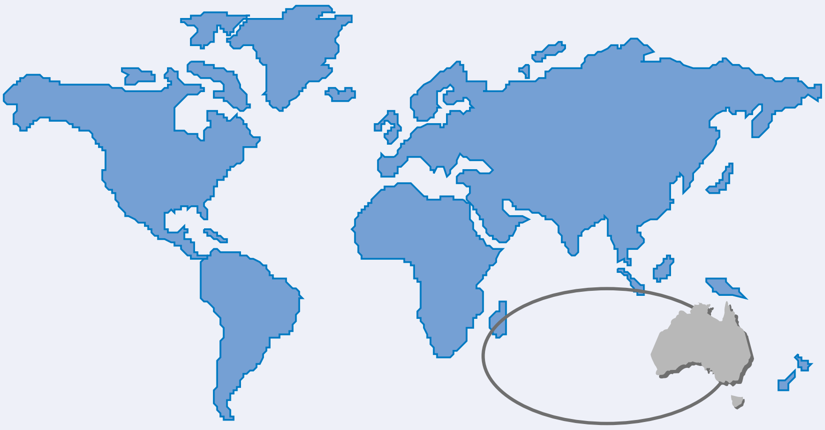
Notes



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