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Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia

Bryson C. Bates · Pandora Hope · Brian Ryan · Ian Smith · Steve Charles

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Abstract Since the mid-1970s the climatic changes that have taken place in southwest Western Australia have generated a variety of impacts, the most prominent of which is a reduction in dam inflows of at least 50 percent. These impacts were the catalyst for the formation of the Indian Ocean Climate Initiative in 1998, a research partnership between two national research organizations and several state government departments and agencies. This paper describes the key scientific findings of the Initiative with respect to the nature of the climatic changes that have taken place within the region, explores the factors that might have caused these changes, and describes the most recent climate projections for the region. We reflect on the factors leading to the rapid acceptance of the research outcomes from the Initiative, the impact of the Initiative on policy development across Australia and its likely evolution post-2006.

Brian Ryan Deceased.

B. C. Bates (✉)
Centre for Australian Weather and Climate Research (CAWCR), CSIRO Marine and Atmospheric Research, Private Bag 5, Wembley, WA 6913, Australia
e-mail: Bryson.Bates@csiro.au

P. Hope
Centre for Australian Weather and Climate Research (CAWCR), Bureau of Meteorology, GPO Box 1289, Melbourne, VIC 3001, Australia

B. Ryan
CSIRO Marine and Atmospheric Research, Private Bag 5, Wembley, WA 6913, Australia

I. Smith
Centre for Australian Weather and Climate Research (CAWCR), CSIRO Marine and Atmospheric Research, Private Bag 1, Aspendale, VIC 3195, Australia

S. Charles
CSIRO Land and Water, Private Bag 5, Wembley, WA 6913, Australia

1 Introduction

In the mid-1970s Southwest Western Australia (SWWA) experienced a change in climate state manifesting itself as a rapid decrease in rainfall and an associated decrease in streamflow. As a result, average inflows to the city of Perth's water supply dams over the last quarter century are well below those of the earlier part of the twentieth century and appear to be decreasing further. This phenomenon was the catalyst for the formation of the Indian Ocean Climate Initiative (IOCI, http://www.ioci.org.au/) in 1998. IOCI is a partnership between two national research organizations (CSIRO and the Bureau of Meteorology Research Centre) and several State partners (government departments and agencies) responsible for natural resources management, providing water services and assisting agribusiness within Western Australia. A discussion of the evolution of IOCI from a strategic partnership with the goals of developing more effective seasonal forecasts and improving understanding of climate variability to a vehicle for assisting decision making and adaptation in climate affected sectors of SWWA can be found in Sadler (2005).

The most recent science plan for IOCI had three key themes: current climate regimes, climate change and climate prediction. The program was designed to progress from the acquisition of knowledge that began in 1998 to the provision of scientific support for the selection of adaptive responses to climate variability and change. To better communicate these outcomes to policy makers, IOCI has distilled key scientific findings into messages relevant to decision and policy making. This included research findings from sources external to the IOCI partnership. A report on recent outcomes is available on the IOCI website (Ryan and Hope 2005).

This paper complements the article by Power et al. (2005) which discussed the influence of IOCI on water planning in Western Australia and some of the challenges that climate scientists face when they try to inform decision makers. The focus of this paper is a discussion of the key scientific findings of the Initiative and their impact on decision and policy making in Western Australia and elsewhere. The next section provides background on the current climate of SWWA. The following four sections describe the climatic changes that have taken place in recent decades, explore the factors that might have caused these changes, present climate projections for the region, and describe how IOCI has influenced policy development in Western Australia and inspired the creation of a similar initiative in southeast Australia. The last section makes some concluding remarks.

2 What is the current climate of Southwest Western Australia?

The southwest corner of Australia is unique in the reasonably high rainfall totals that it receives. Generally, the western edges of landmasses at the latitudes of SWWA (about 30°S to 35°S) receive rather low rainfall, partly because most oceans have an equatorward-directed current along their eastern boundary which, being cool, reduces available atmospheric moisture.

In summer, the subtropical belt of high pressure extends across the region reaching its southernmost extension in January or February. Consequently, summers are dry and hot. During autumn the high pressure belt gradually moves towards the north and lies almost wholly outside the region during the winter months.

Most rain falls within the cooler winter months (June and July) with over 80% falling between the months of April and October (Fig. 1). At this time of year the weather is characterized by moist unstable winds with progressive troughs within a westerly airstream.

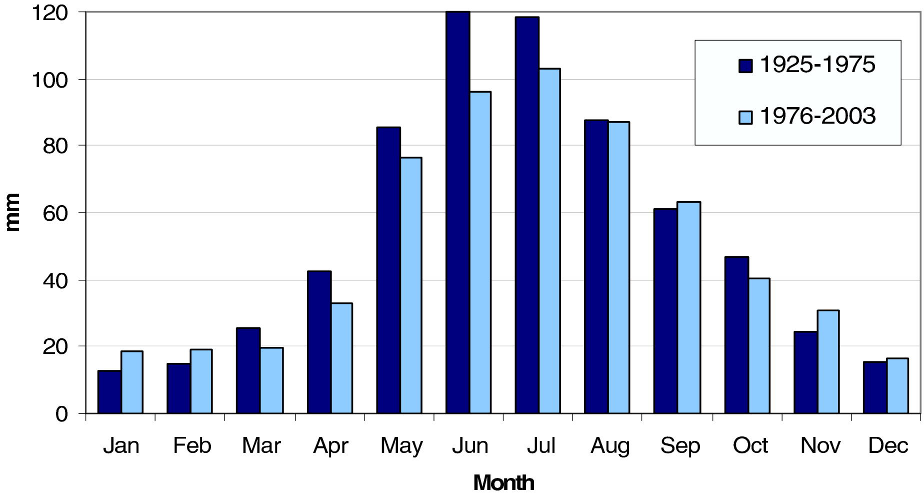

Fig. 1 Average monthly rainfall (mm) for the southwest corner of Australia

The winter climatological trough (Fig. 2) is the most persistent feature of the Southern Hemisphere circulation (Lamb and Johnson 1961). The mean depression track is always south of the region, accounting for the decrease of rainfall from south to north. To the east, mean rainfall decreases rapidly as systems move away to the south-east. Figure 3 shows the mean winter half-year (May to October) rainfall for 1901 to 2000, and illustrates the sharp rainfall gradient from the southwest to the northeast. Consequently, IOCI has defined a region with annual rainfall greater than about 500 mm for calculating spatial averages representative of SWWA. This domain is southwest of the line shown in Fig. 3, which connects the coastline at 30°S to the point (35°S, 120°E). This encompasses much of the region that exhibits lower inter-annual rainfall variability, relative to its total rainfall, than the rest of the continent (Nicholls et al. 1997). It is also distinct from the rest of southern

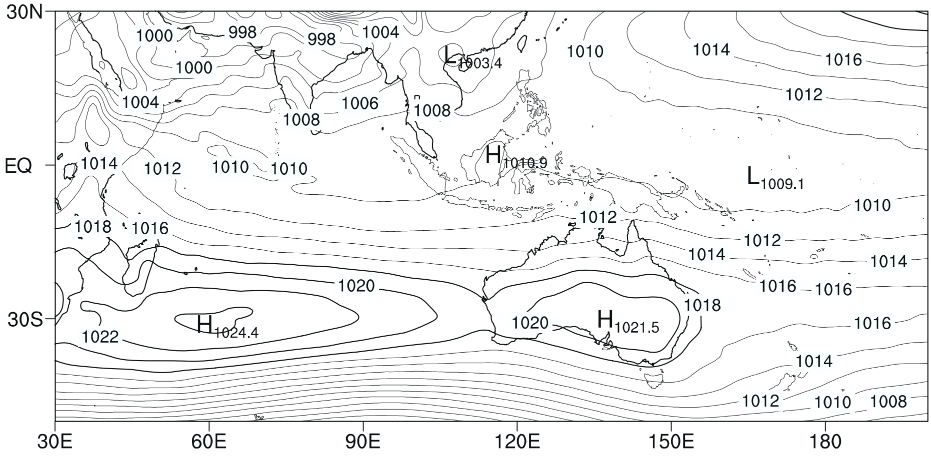

Fig. 2 Average June and July mean sea level pressure (hPa) for the period 1948 to 2002 from NCEP/NCAR reanalysis. Contour interval is 2 hPa

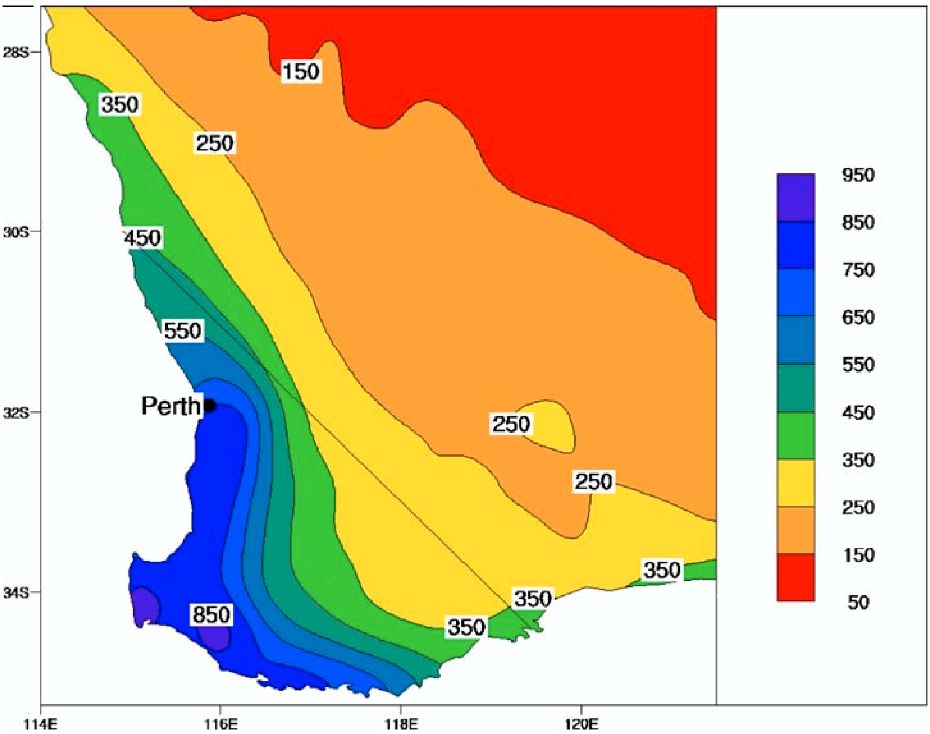

Fig. 3 Mean May to October rainfall (mm) for the period 1901 to 2000. Region southwest of the line connecting the coastline at 30°S to (35°S, 120°E) is used to define spatial rainfall averages for Southwest Western Australia

Australia in that it has experienced a multi-decadal downward trend in winter half-year rainfall (Smith 2004).

3 How has the climate of Southwest Western Australia changed?

As with many regions over recent decades, the climate of SWWA has been characterized by warming. Since the 1970s, annual mean temperatures have increased at a rate of about +0.15°C per decade with increases occurring in all seasons except summer, where cooling of about −0.1°C per decade has occurred. However, one of the most significant climate changes has been the reduction in early winter (May to July) rainfall which took place around the mid-1970s (Fig. 4). The mean totals over the period from 1975 to 2004 are close to 14% less than the means for the period from the mid-1900s to 1974. A major feature of the decline has been the absence of the very high rainfall years which were relatively common throughout much of the last century. While there has been little decline in late winter (August to October) rainfall (Figs. 1 and 4), the most recent data shows that winter half-year rainfall is still relatively low.

One of the major impacts of the rainfall decline has been a reduction in surface water available for storage. The time series of May to April inflows to the region's Integrated Water Supply System is shown in Fig. 5. The average inflow over the period 1911 to 1974 was 338 Gl which almost twice the average of 177 Gl over the subsequent 22-year period

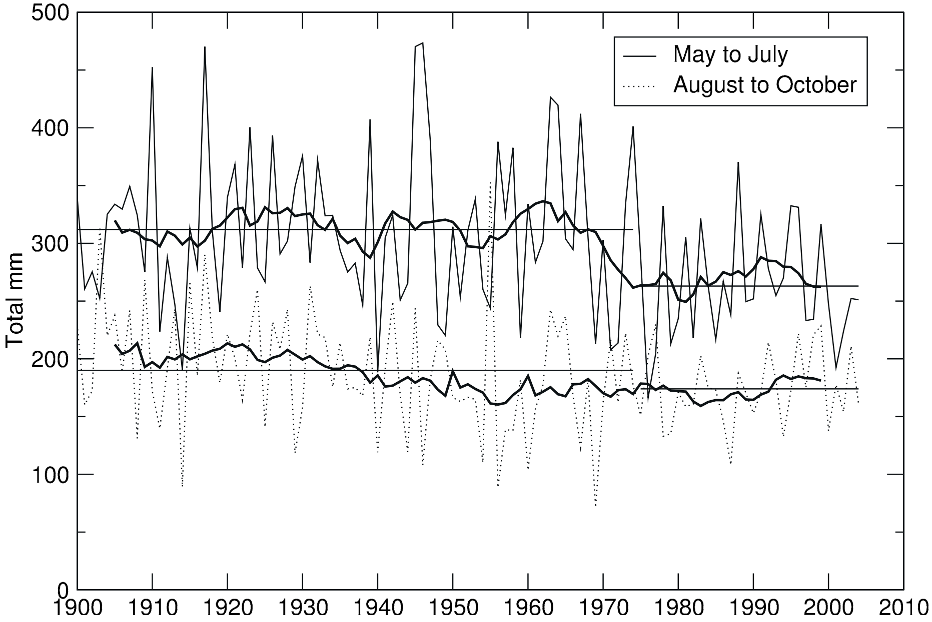

Fig. 4 Time series of Southwest Western Australia rainfall (mm). Solid trace depicts early winter (May to July) totals and dotted trace late winter (August to October) totals. Means for the periods 1900 to 1974 and 1975 to 2004 are represented by horizontal lines

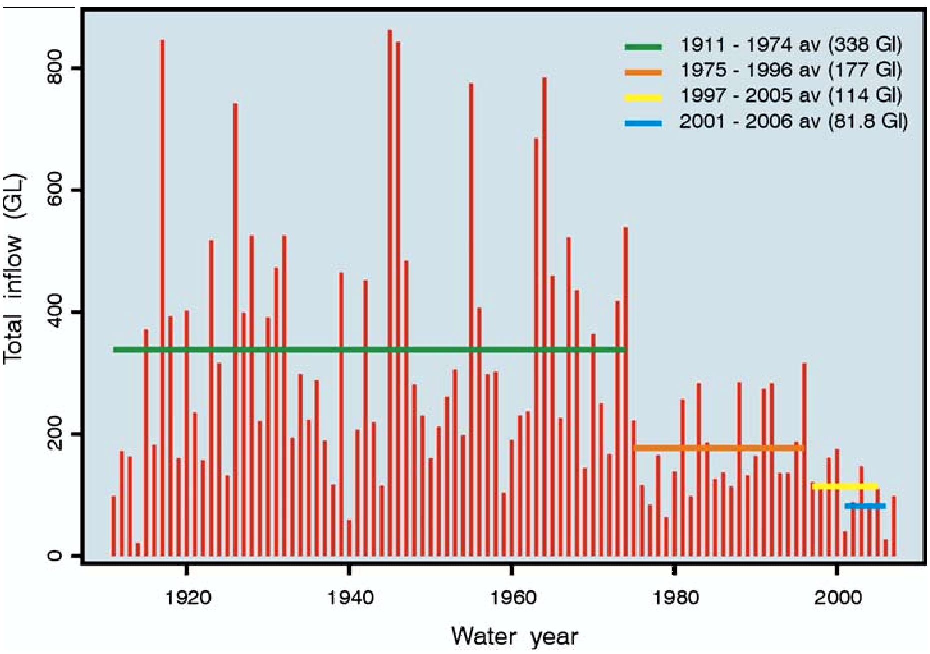

Fig. 5 Annual (May to April) inflow series (GL) for the Integrated Water Supply System. Source: http://www.watercorporation.com.au

(1975 to 1996). Average inflow over the 8 years from 1997 to 2005 was 114 Gl, or close to a third of the 1911 to 1974 average. The inflow from May 2006 to 25 August 2006 is slightly less than 20 Gl. These statistics, and tree deaths due to apparent water stress in the *Eucalyptus gomphocephala* (Tuart) forest in southern SWWA and *Eucalyptus wandoo* woodland in eastern SWWA, have heightened concern that the rainfall decline is intensifying.

In the most recent phase of IOCI emphasis was placed on analyzing shifts in the general circulation on hemispheric to local scales. Analyses of changes in baroclinic instability on the hemispheric scale have revealed a 20% reduction in the strength of the subtropical jet over Australia and an associated reduction in the likelihood of synoptic disturbances developing over SWWA since the early 1970s (Frederiksen and Frederiksen 2007).

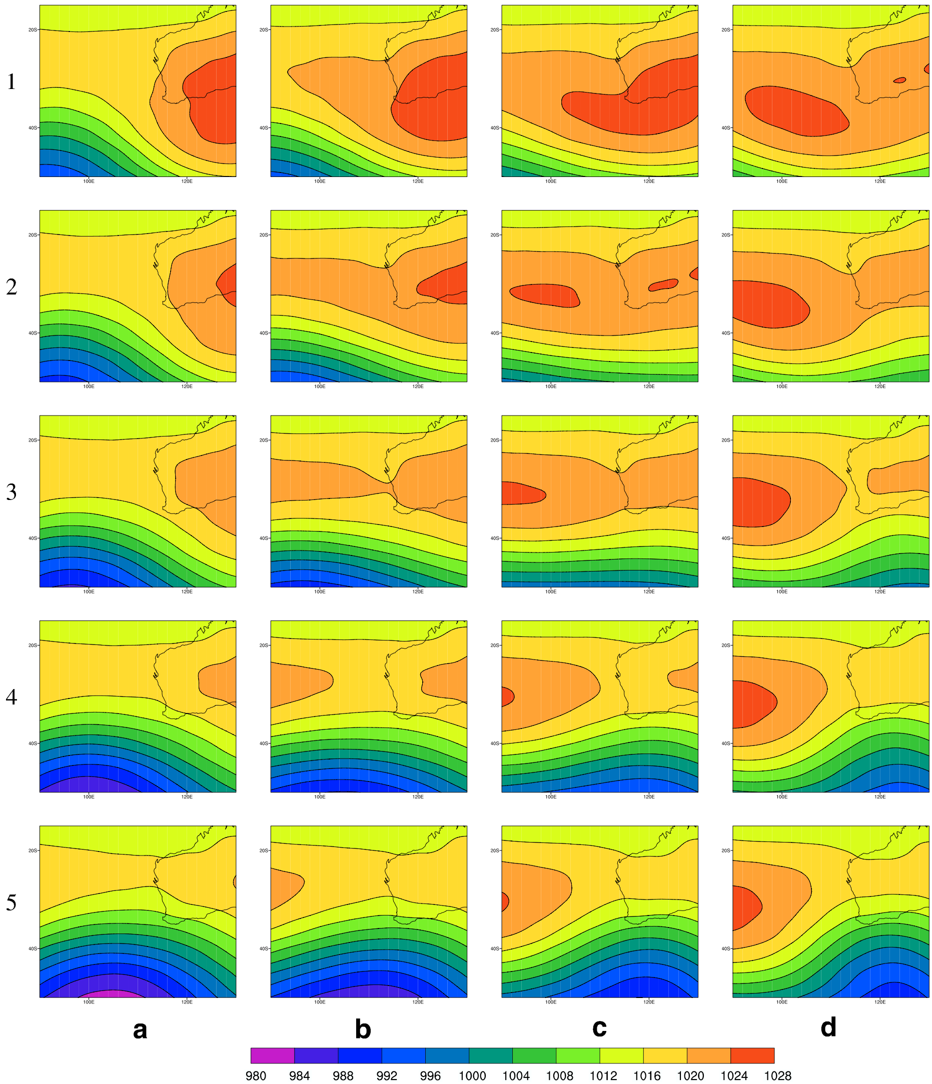

Fig. 6 Twenty synoptic types for Southwest Western Australia identified by the self-organizing map. Red indicates high pressure, blue low pressure. Contour interval is 4 hPa. Source: Hope et al. 2006

At the synoptic scale, a climatology of the early winter synoptic types over SWWA was created (Hope et al. 2006) using the method of self-organizing maps (Kohonen 2001). Twenty types were required to describe the synoptic conditions affecting the region (Fig. 6). The number of deep troughs (along the fifth row of Fig. 6) associated with high rainfall totals in the 1976 to 2003 period is about 17% less than in the 1958 to 1975 period (Fig. 7), contributing to about 50% of the rainfall decline. The *amount* of rainfall from systems with a trough to the west of the continent (left hand column of Fig. 6, Types A2, A3 and A4) has also decreased in the more recent period, contributing a further 30% to the decline. The synoptic types with high pressure over SWWA in the first and second rows are associated with dry conditions. Their frequency increased during the more recent period. However, the decrease in the number of troughs is greater than the increase in the number of high-pressure synoptic types.

At the local scale, two downscaling techniques have been developed to represent daily rainfall at sites across SWWA using atmospheric circulation indices. Timbal (2004) used an analogue technique and found that it reflected the actual rainfall variability and occurrence across SWWA while rainfall taken directly from reanalyses did not. Charles et al. (1999a, b) used a stochastic downscaling method to determine the dominant spatial patterns of rainfall occurrence using daily rainfall series at 30 sites and four atmospheric predictors. Six characteristic rainfall occurrence patterns were found for the winter half-year, and the composited mean sea level pressure (MSLP) patterns on the days corresponding to each rainfall occurrence pattern fall within the range of synoptic types in the self-organizing map obtained by Hope et al. (2006). Two of these patterns and their synoptic and frequency characteristics are illustrated in Fig. 8. The frequency of the pattern corresponding to wet conditions across the western and central areas of SWWA decreased over the period from 1958 to 1975, but it has remained stationary since that time. The frequency of the dry pattern increased abruptly in the mid-1970s and has been increasing ever since.

While the NCEP/NCAR Reanalysis is common to the above analyses, the consistency of the findings from the application of three distinctly different methods (baroclinic instability

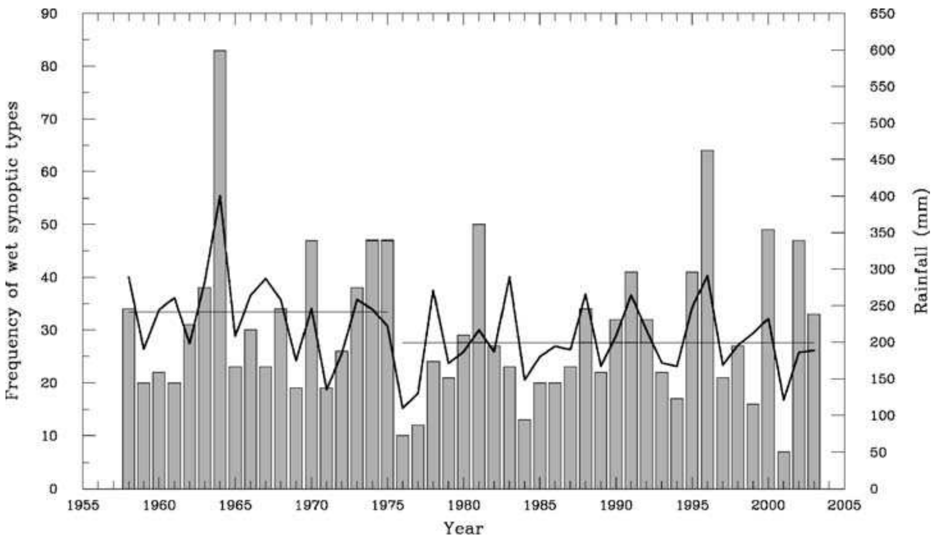

Fig. 7 Spatially averaged rainfall for Southwest Western Australia (bars) and sum of the frequencies of the five 'deep trough' synoptic types from the self-organized map (unbroken line). Source: Hope et al. 2006

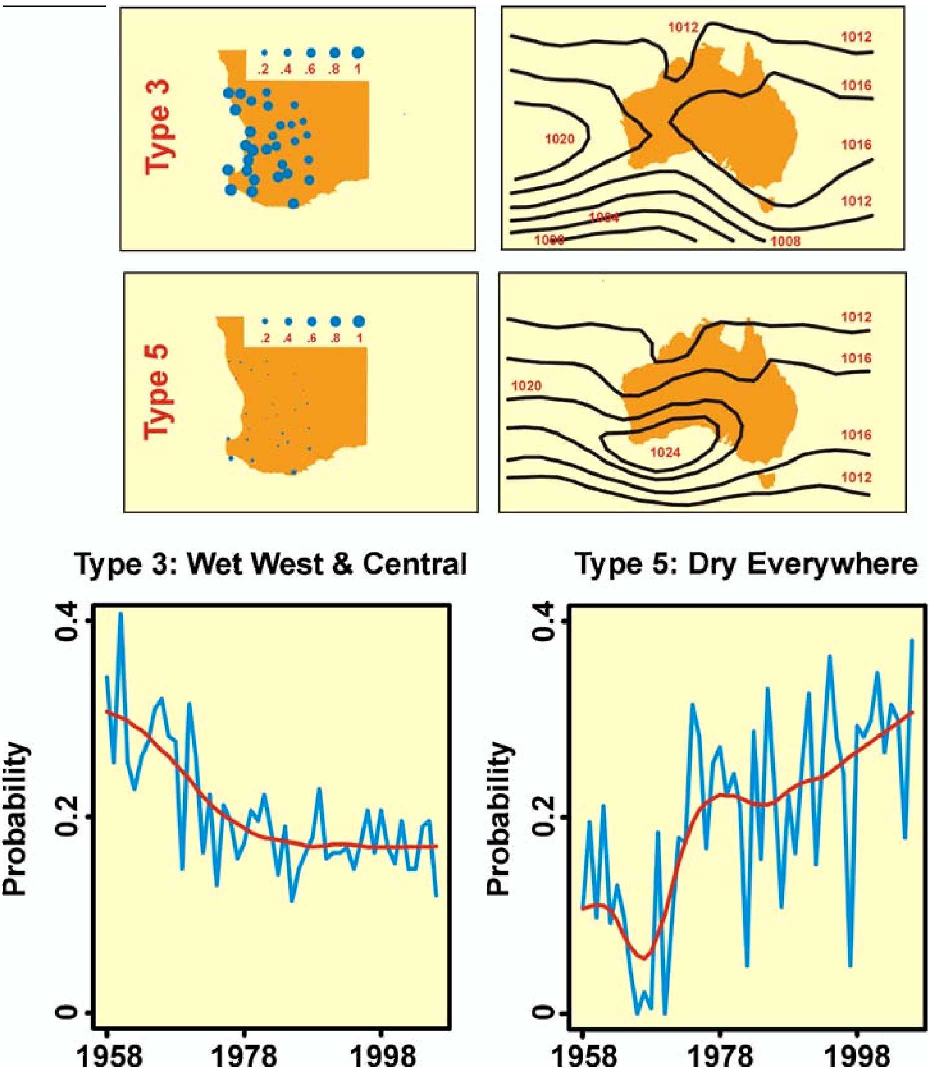

Fig. 8 *Rows 1 and 2* rainfall occurrence patterns and synoptic types associated with wet conditions in western and central Southwest Western Australia (Type 3) and dry conditions (Type 5) for the winter half-year (May–October). *Diameters of blue dots* indicate rainfall occurrence probabilities. *Row 3* time-series of the probability of occurrence of Types 3 and 5. *Red lines* depict robust local smooths of the probability series

theory, self-organized maps and statistical downscaling) on three different spatial scales (hemispheric, regional and local) suggests that the rainfall decline is, at least in part, due to changes in the large scale circulation and synoptic activity.

4 What caused the changes?

Previous studies linking SWWA rainfall fluctuations with those in other parts of the climate system include Wright (1974a, b), Allan and Haylock (1993), Ansell et al. (2000) and Li et al. (2005). Allan and Haylock (1993), for example, examined links with large-scale MSLP, sea surface temperature (SST) and cloudiness patterns. They noted the significant inverse relationship between Perth MSLP and winter rainfall on both interannual and decadal time scales. They also noted the long term warming trend in the Indian Ocean, but subsequent attempts to link the changes in SST to changes in SWWA rainfall have had limited success (Smith et al. 2000; England et al. 2006). Smith et al. (2000) suggested that correlations between SSTs and SWWA rainfall are linked via MSLP while England et al. (2006) also suggested that shifts in the wind patterns drive both SSTs and interannual rainfall variability.

Ongoing efforts to better understand the mechanisms driving the rainfall decline have included analyses of climate model simulations. Simulations in which atmospheric climate models are forced only by observed SSTs over recent decades (so-called “climate of the twentieth century” runs) fail to capture the observed decline in rainfall (see, e.g., Frederiksen et al. 1999). However, an analysis of a 100-year simulation of the CSIRO “Mark 3” coupled ocean-atmosphere model, in the absence of any external forcing (such as changes in the atmospheric concentrations of greenhouse gases), found long-term fluctuations in SWWA winter rainfall somewhat similar to the observed (Cai et al. 2005). This suggests that part of the observed decline in the rainfall could be attributed to natural fluctuations inherent in the coupled atmosphere ocean system.

When coupled models are forced by varying greenhouse gas concentrations (such as those observed over the twentieth century) they also respond in a manner that leads to decreases in simulated rainfall over SWWA. An analysis of twentieth century rainfall simulations from eight different models (Hope 2006) revealed that *all* models capture drier conditions over SWWA after 1975 (Fig. 9). While some of the decreases are not particularly large, their consistency in sign suggests that greenhouse gas forcing may be partly implicated. Timbal et al. (2006) found that the inclusion of several anthropogenic forcings (greenhouse gases, ozone and aerosols) was necessary in order for downscaled simulations

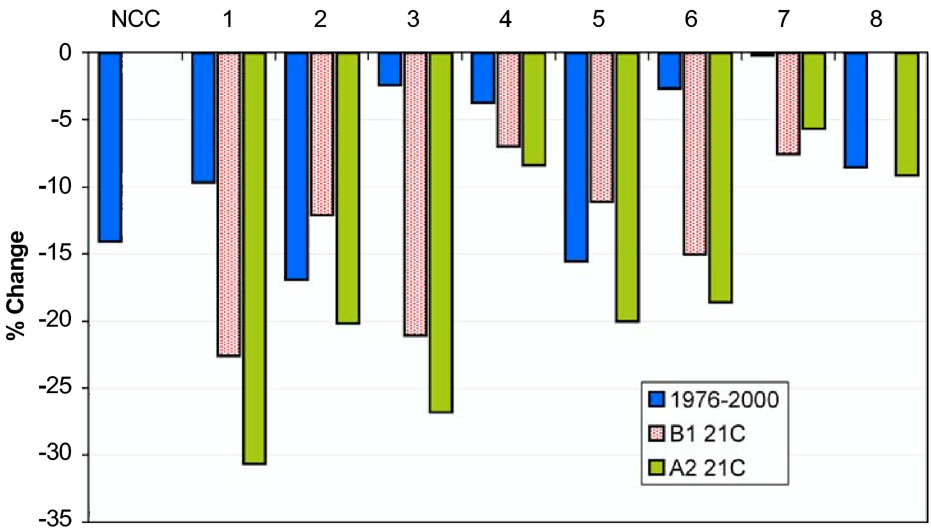

Fig. 9 Percentage changes in June–July rainfall simulated by eight IPCC climate models at grid points closest to Southwest Western Australia for 1976–2000 compared to 1901–1975, and twenty-first century compared to twentieth century, under SRES emission scenarios A2 and B1. *Bar labeled NCC* denotes gridded station data obtained from the National Climate Centre, Bureau of Meteorology. There are no data for Model 8 and the B1 scenario. Data sourced from Hope (2006)

to yield a rainfall decline that approaches the observed. Nevertheless, the simulated decline was only about half the observed. Thus, it is possible that the observed decline could reflect a naturally occurring dry episode supplemented by a relatively small change in rainfall attributable to anthropogenic forcing. The relative contributions are, as yet, difficult to quantify with any precision.

The role of other factors that can be significant at regional scales has also been investigated. Land clearing has been proposed as a contributing factor to the rainfall decline. For two sites east of the regional boundary line shown in Fig. 3, Lyons (2002) has observed that the clearing native of vegetation for agriculture can reduce the occurrence of cloud formation, particularly during the spring months. The reasoning being that changes in surface albedo mean that less radiation is absorbed over the cleared land which reduces the energy available for convection. While this may be a factor in late spring and summer (November–February), observations across SWWA (as defined herein) suggest that a slight *increase* in rainfall has occurred during spring and summer. Furthermore, it is unclear whether albedo changes can be important during late autumn and winter, the time when the observed rainfall decline has been most severe, yet incident solar radiation is relatively low. Consequently, IOCI (2002) concluded that "Most likely, both natural variability and the enhanced greenhouse effect have contributed to the rainfall decrease" and that "Other local factors, such as land-use changes in the southwest…seem unlikely to be major factors in the rainfall decrease, but may be secondary contributors".

More recently, Pitman et al. (2004) used three high-resolution (50×50 km or 56×56 km) regional climate model configurations and boundary conditions for five different Julys to explore the relative effects of land cover characteristics prior to European settlement and those at 1988 on SWWA rainfall. They obtained a reduction in rainfall similar to the observed. The modeled reduction was found to be related to the changes in surface wind strength associated with reductions in surface roughness – a plausible effect that could be significant in winter months. Timbal and Arblaster (2006) also found that the imposition of an unrealistically large change in surface characteristics (four times the spatial extent of the observed) in a climate model experiment reinforced negative rainfall trends due to other forcings. They acknowledged that the magnitude of this imposed forcing meant that they could not quantify the role land clearing in observed rainfall decline.

It is clear that more studies are required to better quantify the relative contributions of multi-decadal variability and anthropogenic forcings such as greenhouse gases, ozone, and land cover change on SWWA winter rainfall. A definitive study will require the use of several climate models at high resolution and experiments that incorporate factors such as: long control simulations for the characterization of multi-decadal variability; the land clearing history of SWWA rather than individual time-slices for pre- and post land clearing conditions; consideration of the complete early winter period (May to July); and comparison of trends in observed and modeled rainfall trends in space–time. However, the resources required such a study would be substantial, if not prohibitive.

5 Modeling future climate: how might the climate of Southwest Western Australia change?

The extended period of dry conditions in SWWA is driving policy and decision makers to prepare for a highly uncertain future. Whether the future holds a return to wetter conditions, continuing dry conditions or further drying is of utmost significance. Projections of future changes are based mainly upon interpretations of the results of coupled climate model runs that incorporate a range of plausible greenhouse gas emission scenarios (Nakićenović et al. 2000). The range of simulated future climates suffers from uncertainty due to a number of sources. To capture some of this uncertainty, it is useful to analyze a number of different models and a range of future emissions scenarios. There is a large and unavoidable uncertainty in the emission scenarios as it is impossible to predict socioeconomic, technological and political conditions in the decades ahead. However, the differences between the projected atmospheric concentrations of CO_2 at 2030, or even 2050, are not very large. An exception is the 450 ppm stabilization scenario, which would require an immediate and large reduction in global emissions.

With a view to exploring plausible futures for SWWA rainfall, climate projections from nine international models were selected on the basis of their ability to reproduce key features of present-day Australian climate, including means and spatial variability patterns of temperature and rainfall. The results also spanned a range of emission scenarios (Table 1). The SRES B2 scenario has relatively low emissions, SRES A2 has high emissions and IS92a has intermediate levels of greenhouse gas emissions. Sulfate aerosol emissions are highest in the IS92a scenario, then A2 and B2. Using the 1960 to 1990 period as a baseline, both the percentage change in modeled mean rainfall and modeled mean temperature at each grid point in each model were linearly regressed against the corresponding global average temperature to account for the climate sensitivity of each individual model. The responses from the different models and scenarios were averaged and then, using the upper and lower bounds on global temperature for a range of SRES scenarios and CO_2 stabilization at 550 ppm and 450 ppm, the local responses in temperature and rainfall were obtained.

The ranges of percentage change in winter rainfall at 2030 are shown in Fig. 10. *All* models and *all* scenarios indicate decreases for the southwest corner of Australia by 2030 with the magnitude of the decrease increasing later in the century. The magnitude of the projected rainfall changes for the SRES emission scenarios are between −2 and −20% by 2030 and between −5 and −60% by 2070. The projections also show a warming for the winter half-year of between +0.5 and +2.0°C by 2030 and between +1.0 and +5.5°C by 2070. During the summer half-year (November to April), increases in temperature are

Table 1 Models and emissions scenarios used to calculate climate projections for Southwest Western Australia

Model	Emission scenarios
Canadian Climate Centre CGCM1	IS92a
Canadian Climate Centre CGCM2	A2, B2 and IS92a
German ECHAM4	IS92a
Hadley Centre HadCM2	IS92a
Hadley Centre HadCM3	A2, B2 and IS92a
CSIRO Mark 2 GCM	IS92a
CSIRO DARLAM (regional climate model) ~125 km resolution (nested in CSIRO Mark 2 GCM)	IS92a
CSIRO Mark 3 GCM	A2
CSIRO Conformal Cubic model ~60 km resolution (nested in CSIRO Mark 2 GCM)	IS92a

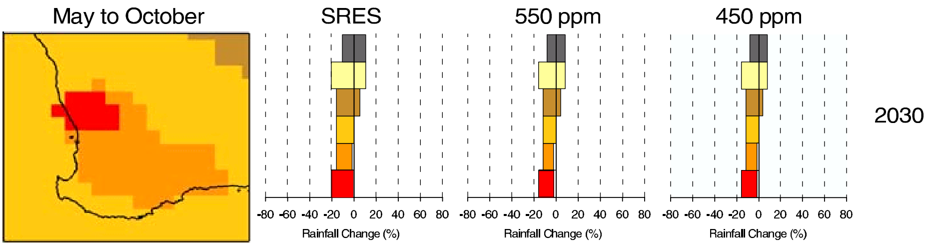

Fig. 10 Projected precipitation changes for 2030 relative to 1960–1990 as determined by runs from nine international climate models forced by the full range of the SRES scenarios and the 550 ppm and 450 ppm stabilization scenarios

projected to reach between +0.5 and +2.1°C by 2030 and between +1.0 and +6.5°C by 2070 (Whetton et al. 2005).

Associated with the temperature and rainfall changes are projected changes in potential evaporation which could be expected to affect soil moisture, surface runoff, and water supply and demand. For the winter half-year and the SRES scenarios considered, potential evaporation is projected to change by up to +10% by 2030 and by up to about +30% by 2070.

The projected rainfall changes are due at least in part to a decrease in the frequency of rain-bearing synoptic systems (Hope 2006). The changes are particularly marked under the SRES A2 scenario, in which gas levels rise to high levels. The percentage changes in modeled rainfall from the twentieth century to the twenty-first century are shown in Fig. 9. Comparing these changes with those seen across 1975 (also shown as a percentage of the twentieth century rainfall), the decline in twenty-first century rainfall represents an additional decline to that already seen since the mid-1970s in the A2 simulations. However the decline is not as strong in the B1 simulations, and in some cases, the decrease is not as strong as in the late twentieth century. The stronger response under A2 forcing is because after about 2070, as the greenhouse gas concentrations escalate under the A2 emissions scenario and dissipate under B1, unprecedented dry conditions are expressed in the A2 simulations while the rainfall remains at about the same (albeit low) levels in the B1 simulations.

Consistent results are obtained using both analogue (Timbal 2004) and stochastic downscaling (Charles et al. 1999a, b). Figure 11 shows projected trends in the probabilities of the 'wet west & central' and 'dry everywhere' synoptic types illustrated in Fig. 8. The probabilities were obtained by downscaling a CSIRO Mark 3 coupled model run based on a SRES A2 scenario with stabilization after 2100. The 'wet west and central' Type shows a consistent decrease in probability of occurrence from the 1980s until some 20 years after stabilization in 2100. From that point there is no apparent trend. The probability of occurrence of the 'dry everywhere' Type correspondingly increases steadily with increasing CO_2, particularly after the early 1960s. Again, the trend dissipates shortly after stabilization in 2100.

6 Impact of IOCI science on policy development across Australia

One of the reasons for the rapid acceptance of the research outcomes from IOCI by the State partners is that they are engaged directly in the formulation of the science objectives and in the evaluation of progress on a regular and ongoing basis. Research providers have

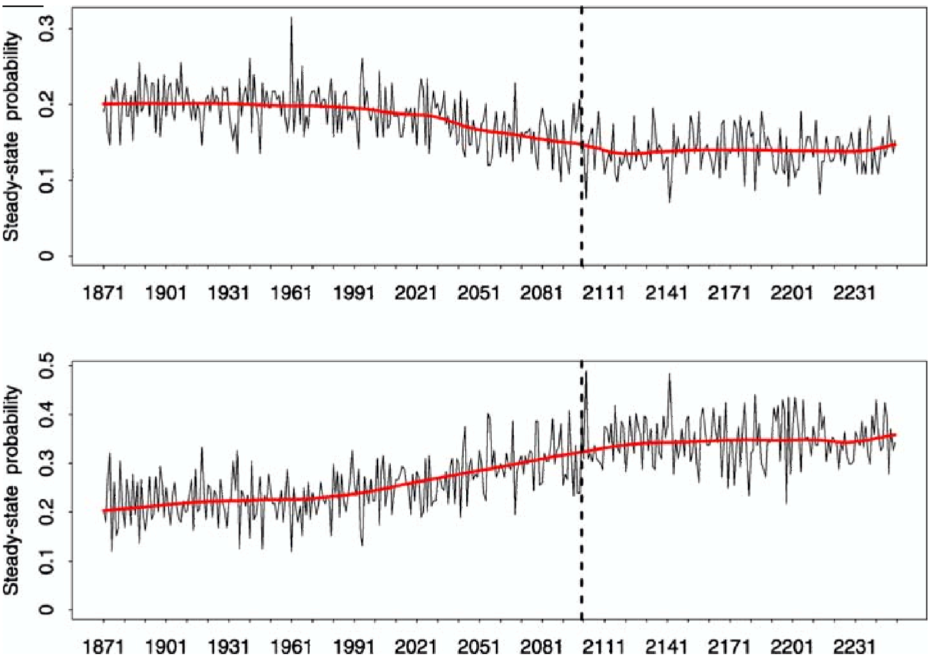

Fig. 11 Simulated probabilities of the 'wet west & central' synoptic type (*Type 3, top*) and 'dry everywhere' (*Type 5, bottom*) obtained by statistically downscaling a CSIRO Mark 3 model run based on the SRES A2 scenario with stabilization after 2100 (*dashed vertical line*). *Red lines* depict robust local smooths of the probability series

benefited from the ongoing feedback and guidance provided by the State, and this has ensured that the results of their work were useful and easily accessible to policy and decision makers. The willingness of researchers to provide such information has led to ongoing financial and 'political' support, and this has ensured the sustainability of the research.

Overall, the research supported and reviewed by IOCI has provided a strong underpinning for policy development. Within Western Australia, the outcomes from the Initiative's research have provided guidance for the State Water Strategy (GoWA 2003). The Strategy states that: "The achievements of the Indian Ocean Climate Initiative have provided an excellent insight into our climate and the continuation of this work will be vital for the achievement of a sustainable water future." Consequently, the Source Development Plan for 2005 to 2050 includes the desalination of seawater, recycling of treated wastewater, improved management of water supply catchments, and water trading as options for improving the security of the State's water supply (Water Corporation 2005). IOCI has provided a strong and acknowledged foundation for the State Greenhouse Strategy (WAGTF 2004). The Greenhouse Strategy supports the notion of 'informed adaptation' by recognizing that: "…our actions can become more focused and effective as we learn more about the issues we are seeking to manage." It proposes action to investigate the risks to agriculture, forestry and biodiversity, and potential adaptation measures. It also recognizes the need for future research into the potential risks for health, tourism, coastal areas and infrastructure. Action 5.4 of the Strategy states: "The Western Australian Government will build upon the IOCI to develop a centre of excellence in knowledge and expertise in climate change in Western Australia." The strategy also notes that the Australian

Greenhouse Office and the Western Australian Government have agreed to cooperatively support the development of integrated strategies for adaptation. To date, several managing climate change projects involving IOCI researchers and State partners have already been initiated in the agricultural and land and water management sectors. Nationally, a recent report from the Australian Greenhouse Office (AGO 2005) acknowledged the contributions to knowledge made by IOCI and identified SWWA as one of six priority regions for the study of climate change impacts and adaptation in Australia. The outcomes of IOCI's research provided the prime source material on SWWA, and its inclusion in the report has firmly established SWWA as a field laboratory for the nation.

The observed change in climate state in SWWA and the emergence of climate trends elsewhere within Australia have heightened interest in projections of a rainfall decline across southern Australia during this century. This concern and the achievements of IOCI have led to the establishment of the South Eastern Australian Climate Initiative which is focused on the water resources of the southeast corner of the Murray–Darling Basin, the southern grains region of the southeast corner of the Australian mainland, and the State of Victoria. The research program for this Initiative is very similar to that encapsulated in the 2003–2006 IOCI Science Plan. The CSIRO and Bureau of Meteorology are involved, as are the Murray–Darling Basin Commission (http://www.mdbc.gov.au/), the Department of the Environment and Heritage through the Australian Greenhouse Office (http://www.greenhouse.gov.au/), the State of Victoria through the Department of Sustainability and Environment (http://www.dse.vic.gov.au/dse/index.htm), and Land and Water Australia (http://www.lwa.gov.au/default.asp).

7 Concluding remarks

The latest suite of climate change simulations show that even with the most optimistic greenhouse gas emission scenarios, SWWA is projected to be drier and warmer later this century with potentially much less water available for storage or for use by agriculture, ecosystems and industry. The current and projected dry conditions suggest that adaptation is an issue for the present rather than the distant future. This challenge has already been taken up by the State of Western Australia.

The current IOCI program will conclude in June 2006. In accordance with Action 5.1 of the State Greenhouse Strategy (2004), a new five-year program is being devised by the research organizations and the State of Western Australia. All parties agree that a central theme must be a strong engagement between the underpinning science and the sector applications that are to be largely carried out by the State. An IOCI-sponsored workshop held in August 2005 also recommended that IOCI should expand the scope of its research to include the Northwest region of Western Australia.

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