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Projected changes in precipitation and the occurrence of severe rainfall deficits in central Australia caused by global warming

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Using an ensemble of 62 simulations with the NCAR CSM 1.4 climate model we have investigated the effect of global warming on rainfall and the occurrence of severe rainfall deficits in central Australia, which receives most of its rain during summer and autumn. For a 'business-as-usual' scenario, results indicate that for the period 2051–2080 compared to the period 1951–1980 there will be a decrease of rainfall in central Australia of about 10 to 20 per cent. In addition, the probability of extreme rainfall deficits is increased. This increase is largest in autumn. In summer, changes in atmospheric circulation, resulting in a more southerly flow advecting dry air into central Australia, appear to be the dominant mechanism for the reduction in rainfall and increase in severe rainfall deficits. The increase in occurrences of southerly flow is caused by the development of a heat low over Australia in response to global warming. In autumn, the reduction in rainfall is due to soil drying. During this season the probability of severe rainfall deficits is significantly enhanced due to the reduction of soil moisture caused by the decrease in rainfall and enhanced evaporation in the preceding summer.

Introduction

In 2002, Australia experienced one of its worst droughts since reliable observation records began. Extremely high temperatures intensified this drought, which was strongest in eastern Australia (Karoly et al. 2003; Nicholls 2004). Drought in Australia is a recurring problem. From 1950 to 2005 five major drought periods have occurred, with a national average monthly rainfall of less than 25 mm/month. All these droughts were associated with higher than normal temperatures but the drought of 2002 had a maximum temperature anomaly which was more than 1°C higher compared to earlier droughts before 2003 (Karoly et al. 2003).

This raises the question of whether these recent droughts are indicative of a changing precipitation climate over Australia and whether droughts will occur more often in the future as a consequence of a warming climate. Studies analysing historical data reveal that over recent decades the total rainfall over Australia has increased but that there are large regional and seasonal differences (Hennessy et al. 1999; Smith 2004; Salinger

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et al. 1996)). Plummer et al. (1999) found that the percentage of Australia experiencing extreme dry conditions (rainfall below the 10th percentile of the annual total) has decreased slightly and the area experiencing extreme wet conditions has increased slightly. This is mainly because of the high rainfall totals in the mid 1970s as well as the high rainfall in Northwest Australia in the last 10 years. Trend maps of precipitation are computed by the Australian Bureau of Meteorology (http://www.bom.gov.au/silo/products/cli_chg/). However, despite the observed changes, Plummer et al. (1999) concluded that the observed climate records are too short to detect statistically significant trends in rainfall, due to the large natural variability.

There is increasing evidence that part of the observed warming over Australia during the last two decades can be attributed to anthropogenic forcing (Karoly and Braganza 2005; Nicholls 2003). Based on different climate model simulations, the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) expects that the temperature in Australia will rise 1° to 6°C by 2070 (CSIRO 2001). The greatest warming is expected to be in spring for most of Australia.

The different climate models vary widely in their results with respect to rainfall. Further, large regional and seasonal differences exist. The annual mean rainfall either does not show a coherent signal or is expected to decrease slightly for most of Australia. Autumn is expected to become wetter for large areas, whereas spring will become generally drier (CSIRO 2001).

Here we present the results of an ensemble of 62 climate simulations with the US National Center for Atmospheric Research (NCAR) Climate System Model (CSM) 1.4 climate model. The climate model is run for the period of 1940 to 2080 forced with a 'business-as-usual' scenario. An ensemble of 62 members is produced. Using a large ensemble it is possible to make a distinction between internal variability and the global warming signal. In addition it enables us to calculate probability distribution functions (PDFs) of rainfall and investigate the changes in these distributions between the present and future climate. In particular, the changes in the tails of these PDFs can be investigated, thereby giving information about the changes in the probability of the occurrence of severe rainfall deficits. This will be the focus of this study.

The structure of the paper is as follows. In the next section the model is described. In following sections, the changes in Australian rainfall and probability of severe rainfall deficits are analysed, and the mechanisms responsible for severe rainfall deficits and how they change as a result of global warming are explored. Finally, a discussion of the results and the conclusions are presented.

Model description

The model used in this study is the 1.4 version of the Community Climate System Model (CCSM) of the US National Centers for Atmospheric Research. The model contains four model components, simulating the atmosphere, ocean, land surface and sea-ice. The atmosphere model was run with a spectral resolution of T31, which corresponds approximately to a horizontal resolution of 3.75°, and 18 levels in the vertical. The ocean component has 25 vertical levels and a 3.6° longitudinal resolution. The latitudinal resolution ranges from 0.9° in the tropics to 1.8° at higher latitudes. No artificial corrections in the heat exchange between the atmosphere and the ocean are applied. The land component distinguishes between specified vegetation types and contains a comprehensive treatment of surface processes.

The simulation period is 1940-2080. Until 2000, the forcing includes specified estimates of temporally evolving solar radiation, temporally and geographically dependent airborne particles (volcanic aerosols and sulphate aerosols due to man-made and natural emissions) and time-dependent major greenhouse gases. From 2000 onwards, all these forcing factors are kept at their year 2000 values, except for the greenhouse gases. These gases increase according to a 'business-as-usual' scenario described in Dai et al. (2001) that is similar to the SRES-A1 scenario of the Intergovernmental Panel on Climate Change (IPCC 2001). A large ensemble of 62 simulations was produced, each differing in a small random perturbation of the initial atmospheric temperature field, while the initial oceanic state was kept the same (Selten et al. 2004 and references therein).

Australian rainfall and simulated changes

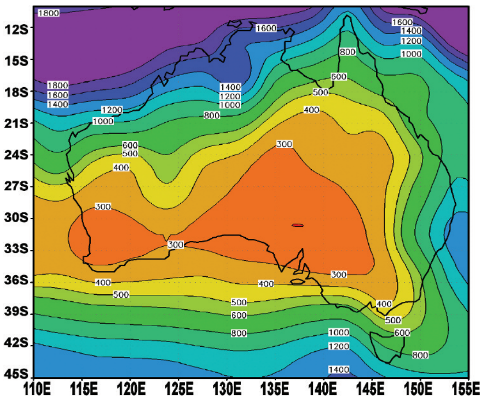
Annual mean

The simulated mean annual rainfall over Australia for the period 1951-1980, averaged over the 62 ensemble members shown in Fig.1(a), reveals a similar pattern as observed (Fig. 1(b)), with large rainfall in the northern tropics and dry conditions in central and southern Australia. The largest differences occur along the eastern coast where the heavy observed precipitation is not simulated by the model, probably because the horizontal resolution is insufficient to resolve the orography. For most parts of Australia the simulated rainfall is slightly overestimated in comparison with the observations.

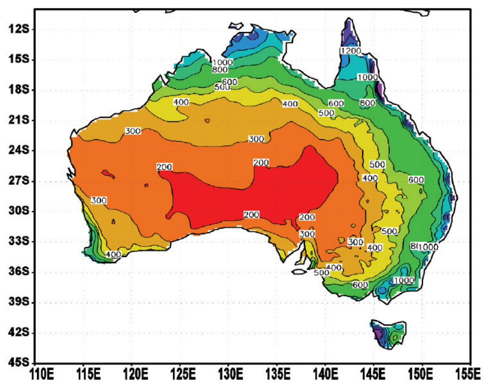
The simulated changes in mean annual rainfall for Australia are presented in Fig. 2 (upper panel), which

Fig. 1 **Average annual rainfall (mm) for 1951-1980 for (a) the simulated ensemble mean and (b) observed rainfall (Australian Bureau of Meteorology).**

(a)

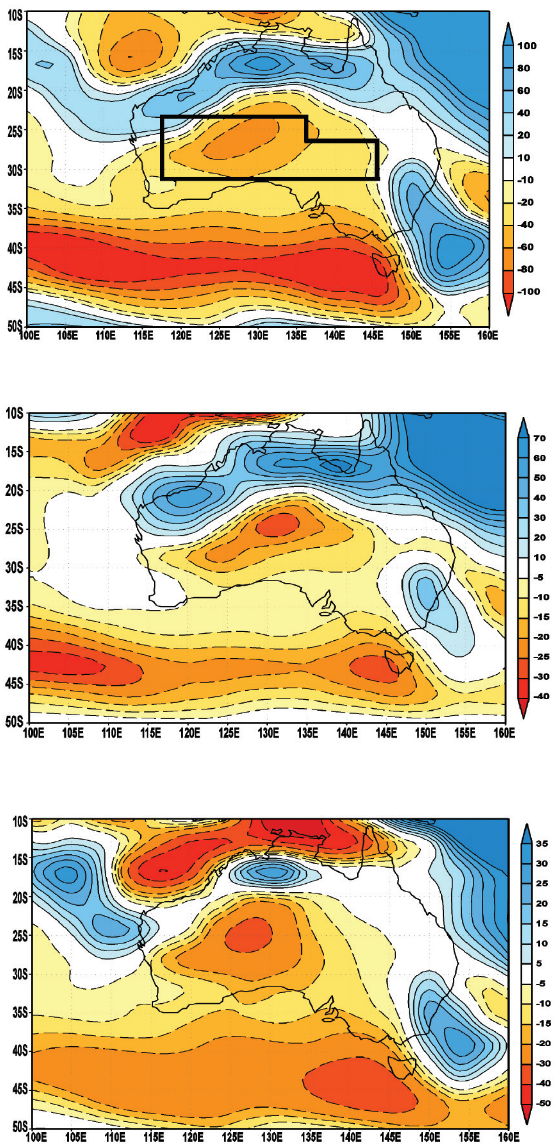


(b)



shows the difference in the ensemble mean annual rainfall between the periods 2051-2080 and 1951-1980. Positive differences indicate a wetter regime under greenhouse-induced warming, while negative differences indicate a drier regime. The simulated change in rainfall over Australia reveals strong spatial differences. The northern and southeastern part of Australia become wetter, with a maximum increase of more than 100 mm/year near Timber Creek, whereas the central and southern part of Australia become drier, with a decrease of more than 60 mm/year in central Australia. These simulated regional changes compare roughly with the regional differences in the observed climatological rainfall. In general the regional differences in precipitation over Australia will increase: wet regions will become wetter and dry regions will become drier.

Fig. 2 **Simulated change in ensemble mean rainfall between 2051-2080 and 1951-1980 (mm) for the annual mean (upper panel), summer mean (DJF) (middle panel) and autumn mean (MAM) (lower panel). Dashed contours indicate negative values. Positive differences indicate a wetter regime under greenhouse-induced warming, while negative differences indicate a drier regime.**



Summer and autumn mean

In the tropical northern part of Australia, as well as the dry inner part of Australia, most of the rain falls during the summer. The difference in rainfall between

2051-2080 and 1951-1980 for the summer months DJF, shown in Fig. 2 (middle panel), is similar in pattern to the annual difference.

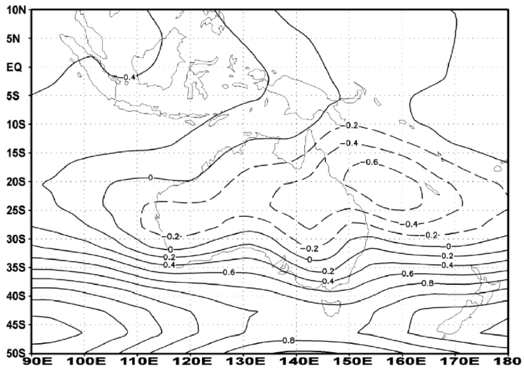
Wardle and Smith (2004) suggest that the Australian monsoon will increase during global warming due to the development of a heat-low over Australia. Our results indicate a similar mechanism. The increase in surface air temperature (SAT) over the Australian continent is approximately 1.5°C, which is about 0.5°C more than the increase in SAT over the surrounding oceans. As discussed in Haarsma et al. (2005) the enhanced continental heating compared to the oceans in this model is due to the larger increase in low-level clouds over the oceans. An additional effect for Australia is the reduction of latent heat flux due to soil drying. Over central Australia the reduction is about 5 Wm^{-2} (~10 per cent). The changes in the mean sea-level pressure (MSLP) pattern for summer shown in Fig. 3, with a decrease over most of Australia, are in agreement with the hypothesis of a decrease in MSLP due to an enhancement of SAT over Australia. This anomalous MSLP pattern enhances the Australian monsoon, with increased rainfall over northern Australia due to the advection of more moisture by westerly winds from the Indian Ocean. The heat low also induces anomalous easterlies in southeastern Australia. The increased moisture advection and orographic ascent over the Great Dividing Range caused by these winds explain the increased rainfall in southeastern Australia.

The anomalous MSLP pattern also contributes to the reduction in rainfall over central Australia due to the advection of dry southerly winds. Analysis of the moisture budget reveals that $v'.\nabla q$, (i.e. the advection of mean moisture q by the anomalous wind v') is reduced over this area. Over central Australia there is increased descent in the later period compared with the earlier period, as revealed by the 500 hPa vertical velocity (not shown). This further reduces the rainfall. The change in rainfall for the autumn months MAM is displayed in Fig. 2 (lower panel). Compared to the summer the increase in rainfall over northern Australia is less, whereas the decrease over central Australia is more widespread. The latter is due to the drying of the soil, as we will discuss below.

Interannual variability

The model simulation shows a reduction in rainfall over central Australia. This area is characterised by very little rainfall, which mainly occurs during the summer. In the remainder of this paper we will focus on this area, indicated in Fig. 2 (upper panel) by a box (referred to as central Australia). This box has been selected by inspecting the rainfall data of the Australian Bureau of Meteorology (http://www.bom.gov.au/silo/products/cli_chg/rain_timeseries.shtml). In Fig. 4, the ensemble-mean simulated mean monthly rainfall averaged for central Australia is shown together with the observations computed from the gridded data-set of the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/averages/climatology/gridded-data-info/gridded-info.shtml). In the observations the largest rainfall occurs during the summer months January and February, whereas the driest period is late winter (August-September). This annual cycle is to a large extent also simulated by the model, although the summer rainfall is significantly overestimated by the model. Figure 4 also displays the simulated monthly rainfall for the period 2051-2080. In particular, the wet summer months will become drier in the future. The largest changes, of the order of 5 mm (10-20 per cent), occur during the months January to May.

Fig. 3 **Simulated ensemble mean change in MSLP (hPa) between 2051-2080 and 1951-1980 for summer (DJF). Negative contours are dashed.**



For the investigation of severe rainfall deficits we will concentrate on summer (DJF) and autumn (MAM), which are the seasons showing the largest changes in rainfall. The black dots in Fig. 5 reveal the large interannual variability of central Australian rainfall in summer simulated by the model. Note that because of the averaging the ensemble mean (black line) shows a much reduced interannual variance. For better comparison with the observed variability (grey line) we have also drawn the annual rainfall of an individual ensemble member (member #12, dashed line). The variability of the model appears to be comparable with the observed variability. The ensemble mean rainfall in summer shows a downward trend starting at the end of the 20th century. The summer rainfall in 2080 is around 10 per cent less compared

Fig. 4 **Monthly rainfall (mm) averaged over central Australia: observed for the period 1951-1980 (triangles), simulated ensemble mean for the period 1951-1980 (diamonds) and for the period 2051-2080 (squares). Month number 1 is for January and 12 for December.**

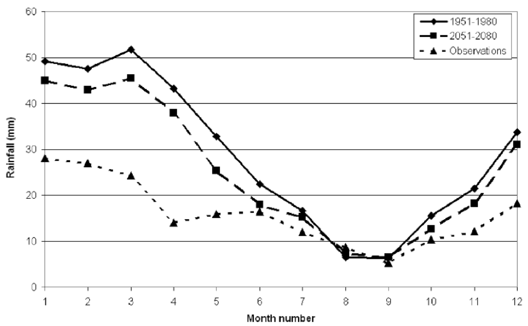
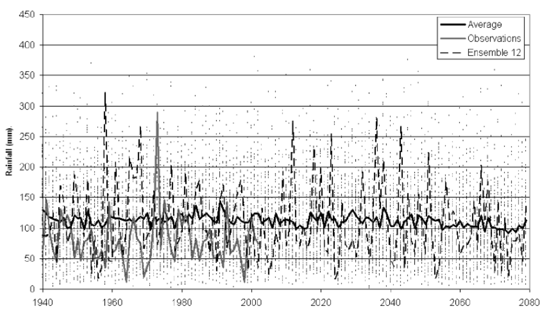


Fig. 5 **Rainfall of central Australia for DJF for each of the 62 simulations (dots), ensemble mean (black line) and observations (grey line, up to summer 2001/2002). The rainfall of ensemble member 12 is indicated by the dashed curve.**



with 2000. A similar large interannual variability and decrease in the ensemble mean rainfall is also observed for autumn (not shown).

To answer the question of whether severe rainfall deficits will occur more often in the future, changes in the structure of the PDF of rainfall have to be taken into account. These are depicted in Fig. 6 for summer and autumn. They show that for summer there is a rather uniform shift towards conditions with less rainfall, whereas for autumn there is a clear change in the structure of the PDF, with an enhanced probability of severe rainfall deficits. The changes in mean and 5th and 95th percentiles for both seasons are given in Table 1. The change in the mean in autumn is larger than in summer. In addition the change in the 5th percentile is about twice for autumn than for summer. Table 1 shows that for both seasons the probability of severe rainfall deficits will increase, but that the increase will be larger for autumn than for summer. Below we will investigate the causes for the increased probability of severe rainfall deficits.

Severe rainfall deficits in central Australia

Causes for severe rainfall deficits

To investigate for the ensemble the relation between the atmospheric circulation and severe rainfall deficits an average MSLP pattern is constructed from the driest summer seasons in 62 members (lowest 20 per cent) during the period 1951-1980 (see upper panel of Fig. 7). This average anomaly pattern shows a higher than normal pressure belt over the ocean just west of the west coast of Australia. This pattern bears similarity to the average MSLP pattern for the 20 per cent driest observed summers (which is six years in order of severity: 1964/1965, 1969/1970, 1958/1959, 1970/1971, 1978/1979, 1951/1952) during the period 1951-1980 (lower panel of Fig. 7) as obtained from the NCEP-NCAR reanalysis (Kalnay et al. 1996). The lowest 20 per cent were needed because of the short-

Table 1. **Changes in the structure of the PDFs of rainfall over central Australia for summer (DJF) and autumn (MAM) (mm).**

	1950-1980		*2050-2080*		*Difference*		*Relative*	
	DJF	*MAM*	*DJF*	*MAM*	*DJF*	*MAM*	*DJF*	*MAM*
Average	113	111	104	96	-9	-15	-8%	-14%
5th percentile	28	38	22	24	-6	-14		
10th percentile	41	48	34	35	-7	-13		
90th percentile	199	176	185	166	-14	-10		
95th percentile	225	190	220	184	-5	-6		

Fig. 6 Frequency distribution of the rainfall in central Australia for 1951-1980 (solid line) and 2051-2080 (dashed line) for DJF (upper panel) and MAM (lower panel). The average rainfall for both periods are indicated by (diamonds) and (triangles) and the 5th and 95th percentiles by vertical lines.

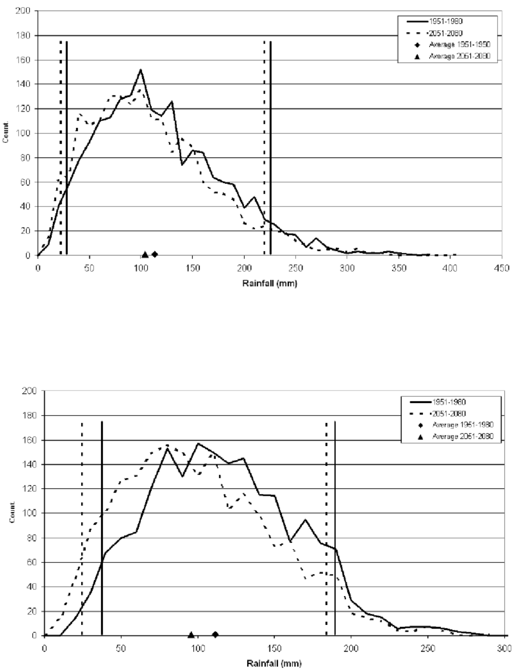
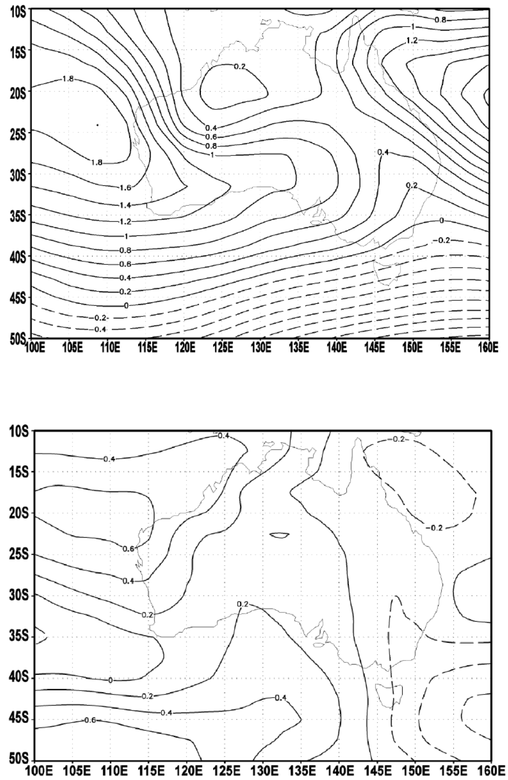


Fig. 7 Upper panel: anomalous MSLP averaged over the 20 per cent driest DJF seasons simulated by the model. Anomalies are based on the climatological average of 1951-1980. Lower panel: similar to the upper panel but now over the 20 per cent driest DJF seasons (six seasons) in the NCEP-NCAR reanalysis.



ness of the data-set with observations. Added to this, it seemed that the patterns calculated with the model are not very sensitive to the choice of the number of dry seasons. Both patterns result in an anomalous flow from the south which advects less moisture into central Australia. To investigate the relationship of the meridional flow over central Australia with the rainfall in that region for other years, we plotted in Fig. 8, for all summer seasons of the ensemble, the meridional wind *V* against the seasonal rainfall. From this figure it is clear that southerly (northerly) flow values correspond with less (more) rainfall. Repeating the above analysis for autumn (not shown), the average anomalous MSLP pattern for the 20 per cent driest autumns reveals a pattern somewhat different from summer's pattern. The advection of dry air into central Australia is less clear and, in contrast to the summer, no clear relationship between meridional wind and rainfall has been found for the autumn. This indicates that in the model less rainfall in autumn is not primarily caused by anomalous southerly flow. In the model as well as in the observations the flow is predominantly northerly during autumn, whereas during summer it is much more variable between southerly and northerly flow. This might explain why there exists a clear relationship between *V* and rainfall in summer and not in autumn. In summer, changes in seasonal mean *V* are related to different source regions (dry subtropics versus wet tropics), whereas in autumn this is not the case.

Another factor that might affect rainfall is soil moisture. Timbal et al. (2002) demonstrated the importance of soil moisture for climate variability over Australia. In particular at the end of the summer, drying of the soil can initiate and maintain drought conditions (Gregory et al. 1997). Indeed in the model there is a weak relationship between the central Australian soil moisture content in summer and the central Australian rainfall in autumn. The correlation

Fig. 8 **Scatter plot of the meridional wind *V* and rainfall over central Australia in DJF for 1951-1980. Black, and dashed, lines are the quadratic regression lines for 1951-1980 and 2051-2080 respectively. Southerly (northerly) winds are associated with positive (negative) *V* components and decreased (increased) rainfall.**

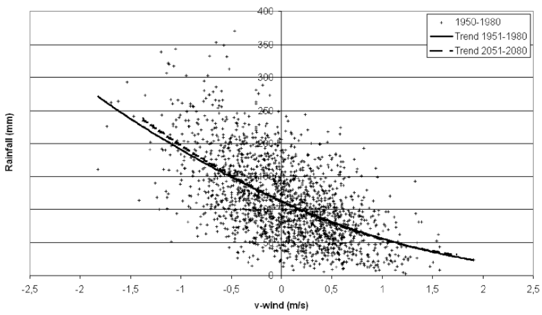
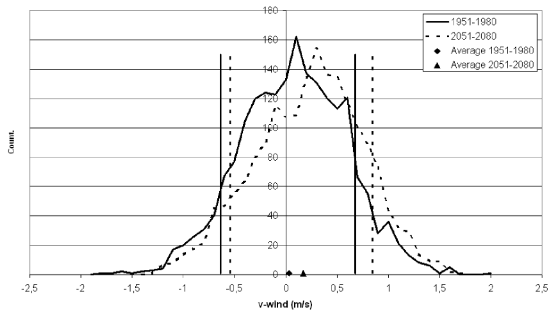


Fig. 9 **Frequency distribution of the meridional wind *V* over central Australia in DJF for 1951-1980 (solid line) and 2051-2080 (dashed line). The average of *V* for both periods are indicated by (diamonds) and (triangles) and the 5th and 95th percentiles by vertical lines.**



between these two variables is 0.3. This means that drier soil in summer leads to reduced rainfall in the following autumn season. The relationship is much stronger in the events of severe rainfall deficits. For the driest autumn seasons (lowest 10 per cent in 62 members for the 1951-2080 period) the soil moisture content of the preceding summer season was less than the average soil moisture content in 80 per cent of the cases. Also, for these driest autumn seasons the soil moisture attained its minimum value of the annual cycle (not shown). This strongly indicates that severe rainfall deficits in autumn are related to a shortage of soil moisture.

Such a relationship is not found between the soil moisture content of spring (SON) and the rainfall in summer, which strengthens the conclusion that rainfall in summer is predominantly determined by the atmospheric circulation.

Mechanisms responsible for the increase of severe rainfall deficits during global warming

Summer

In the previous section it was found that severe rainfall deficits in central Australia during summer are related to a characteristic pressure anomaly pattern (Fig. 7) that advects dry air from the south into this region. In order to determine whether a southerly flow occurs more often in the presence of global warming we computed in Fig. 9 the PDF of the meridional wind over central Australia for the periods 1951-1980 and 2051-2080. This figure shows a shift of the distribution to a more southerly flow. We also checked whether in a warmer climate southerly flow is still related to severe rainfall deficit conditions. Indeed, also for the period 2051-2080, the regression is very similar to the regression for the period 1951-1980 (Fig. 8). From this we conclude that changes in the atmospheric circulation contribute to the increase in drought conditions during summer. Similarly to the 1951-1980 period, no significant relationship exists between moisture in spring and rainfall in summer for the period 2051-2080.

Autumn

As discussed before, severe rainfall deficits in autumn appear to be related to the soil moisture content in the preceding summer. We therefore suppose that a reduction in soil moisture during summer caused by global warming contributes to the increase in severe rainfall deficits during autumn. Figure 10, showing the change in the soil moisture in summer, reveals that the average soil moisture content for 2051-2080 in central Australia has been reduced by about 10 per cent compared with 1951-1980. Similarly to the 1951-1980 period, dry autumn seasons in 2051-2080 are also related to low soil moisture content in summer. For the 10 per cent driest autumn seasons the soil moisture content of the preceding summer season was less than the average soil moisture content in 78 per cent of the cases. From this we conclude that the decrease in soil moisture in summer enhances the probability of severe rainfall deficits in autumn. Similarly to the 1951-1980 period, severe rainfall deficits in 2051-2080 appear not to be strongly related to a specific atmospheric circulation pattern.

Discussion and conclusions

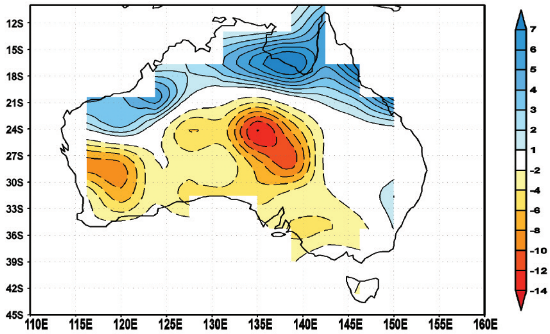
The results of an ensemble of 62 climate simulations with the NCAR CSM 1.4 climate model indicate that in the case of global warming, the annual rainfall in the wet northern tropical parts of Australia will increase, whereas it is expected to decrease in central Australia. This decrease is mainly caused by a decrease in rainfall in summer (DJF) and autumn (MAM). In both seasons the average rainfall is expected to be 10-20 per cent less in the latter part of the 21st century compared with the latter part of the 20th century in a 'business-as-usual' scenario. Also the chances of extremely dry summers and autumns are expected to increase. In particular, for autumn there is a significant increase in the probability of severe rainfall deficits.

Our results indicate that in summer severe rainfall deficits in central Australia are related to a circulation pattern that advects a southerly flow of dry air into the region. The southerly flow will occur more often in the future resulting in an increase in severe rainfall deficits. The increase in the probability of southerly flow is related to the heat-low response over Australia caused by the enhanced continental heating, which induces an anomalous southerly flow over central Australia. This change in the atmospheric circulation induces a shift in the PDF without a significant change in the shape. For autumn, the significant increased probability of severe rainfall deficits appears to be related to a shortage of soil moisture. A severe rainfall deficit in summer will reduce the soil moisture availability and therefore increase the probability of the occurrence of a severe rainfall deficit in autumn. The shortage of moisture induces a positive feedback with severe rainfall deficits. The consequence of this is that additional to the shift in the PDF, its shape also has been changed, resulting in an enhanced probability of severe rainfall deficits.

Until now no reduction in rainfall in central Australia has been observed. On the contrary, most studies indicate an increase in rainfall over this region (Suppiah and Hennessy 1998; Hennessy et al. 1999; Smith 2004) over recent decades. Whether this is a greenhouse signal, in contrast to the model simulations, or internal variability is an open question as the model simulations indicate that the reduction in rainfall over central Australia should become noticeable during the second half of the 21st century (Fig. 5). In addition, as Smith (2004) points out, central Australia is a data-sparse region which makes the observed trend less reliable.

Rainfall is one of the most difficult variables to simulate and projected changes in rainfall over

Fig. 10 Percentage change in the average ensemble mean summer soil moisture content of 2051-2080 with respect to 1951-1980.



Australia caused by global warming differ widely. The projected change in rainfall during summer and autumn in the southern inland of Australia based on a suite of different climate models varies from -35 per cent to 60 per cent (CSIRO 2001). This underlines the caution that should be taken in the interpretation of the results of this study. We do, however, claim that the connection of severe rainfall deficits with circulation patterns and soil moisture as discussed in this article is valid and therefore adds to our understanding of how the frequency of severe rainfall deficits may change due to global warming.

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