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The rainfall response to permanent inland water in Australia

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Schemes to produce permanent inland water surfaces in central Australia to ameliorate the climate in agricultural areas have been suggested since the late 19th century. A thorough examination of the expected meteorological response to such an imposed water expanse was undertaken by Warren (1945) and the general conclusion was that there would be limited change to the climate. Here we use data and techniques not available to Warren (1945) to assess the likely impact of large permanent inland water surfaces on Australian rainfall. Studies of the rainfall response to extensive areas of irrigation in other countries generally conclude that there is little discernible difference in the rainfall amount, and the rainfall pattern does not change. Inland Australia is arid, with strong potential evaporation and only intermittent rainfall from modifications to the large-scale flow, often linked with positive phases of the El Niño – Southern Oscillation (ENSO). ENSO is also strongly linked with rainfall in eastern Australia, most likely swamping any signal from an inland water source. The large-scale interaction between the atmosphere and the land surface in central Australia is weak, and is not affected by whether large lakes such as Lake Eyre are full. Both mesoscale and global climate models show that large water expanses do have local effects including a large local increase in surface latent heat flux and a decrease in temperature. In some cases this reduces rainfall over the water surface. The variable-resolution version of the CSIRO conformal cubic atmospheric model, with a fine grid of approximately 60 km over Australia, and the Melbourne University General Circulation Model are both used to assess the wider response to a large inland water expanse. Away from the imposed water expanse there is no consistent or significant response in rainfall anywhere in Australia. We conclude, as did Warren (1945) that there is no evidence that large-scale permanent water surfaces in inland Australia would result in widespread climate amelioration.

Introduction

'Drought-proofing' Australia is a concept that fires the imagination of the Australian people, particularly during severe drought. One recurring suggestion to achieve this aim is to form a large water expanse in central Australia, with the assumption that moisture evaporating from such an expanse would later precipitate over agricultural regions in eastern Australia.

This premise then opens the debate as to whether such a large water expanse would actually modify Australia's rainfall regime. This question has been asked before, and as reported in Warren (1945) the usual conclusion has been that there would be minimal change. There are now longer data records than

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were available to Warren (1945) and climate models can be used to test the effect of a large water expanse, so a re-examination of the question seems timely.

Problems with building such a water expanse include the cost and environmental impacts. None of these problems will be addressed here; this study is designed solely to address the question of whether a large inland water expanse, particularly in the region of Lake Eyre, would produce a strong rainfall response somewhere, and if so, where and by how much.

In this paper we first provide a brief overview of some of the historical suggestions for increasing water surfaces in inland Australia, followed by a description of the physical geography of Lake Eyre and its catchment and the climate of the region. We then present a review of some of the literature about the results from flooding large regions in other parts of the world followed by a brief discussion of the strength of the interaction between the surface and the atmosphere in the Eyre catchment through the recycling of rainfall over central Australia. The results of modelling studies of the impact of increased water surfaces in central Australia are then presented, followed by our conclusions.

Early schemes and analysis

There have been several proposals to increase permanent water surfaces in inland Australia since Australia's European settlement. These proposals have included schemes involving broad channels from the south coast, damming some of the rivers that feed Lake Eyre from the north, or building pipelines from high rainfall areas on Queensland's coast. A proposal to fill Lake Eyre, the largest ephemeral salt lake in Australia, was first discussed by the South Australian Government in the late 1800s, but it was not pursued. Many of the early schemes are documented in Towner (1955). The best known proposal was the 'Bradfield Scheme' outlined in 1941.

The Bradfield Scheme proposed massively increased inland water storage and irrigation through southwest Queensland and northern South Australia. To achieve this, a series of pipes and dams would redirect tropical rainfall from the east of the Great Dividing Range to storages in the west. Ion Idriess, an author and traveller, proposed a similar scheme (Idriess 1946). At the time, both the Bradfield and Idriess schemes received considerable public support (e.g. Timbury (1944)).

Bradfield's belief that inland water storage would ameliorate the climate of inland Australia was based on the research of Quayle (1921, 1922). Quayle (1921) explains how a surface water source such as Spencer Gulf, irrigation, or a full lake would lead to rainfall downwind. Most of his analysis is of areas that derive much of their rainfall from frontal systems embedded in the prevailing westerlies, south of the subtropical ridge. Quayle stated that much of the response was due to the air generally being near a threshold level of humidity; thus only a small addition was needed to help trigger an increase in precipitation. Lake Eyre is further inland than the sites mentioned above and conditions are a little different - the seasonal precipitable water totals created with NCEP-DOE (National Centers for Environmental Prediction – Department of Energy) Reanalyses II (Kanamitsu et al. 2002) show that the amount of water in the atmosphere is less at Lake Eyre than at Spencer Gulf during winter and autumn as well as being more vertically stable, with less potential for storms, over Lake Eyre in all seasons except autumn.

Quayle also examined the rainfall to the southwest of the inland Lakes Torrens and Frome. Although there was evidence of an increase in rainfall when the lakes were full, this matched rainfall increases in the larger region, suggesting that the large-scale conditions leading to the lakes filling also produce rain across the wider region. The statistics from Quayle's studies also suffer from the problem of having been produced from only a short period of data, a problem exacerbated by the strong interannual variability of inland rainfall.

A committee of meteorologists from the University of Melbourne and the Commonwealth Meteorological Bureau examined the Bradfield proposal and their conclusions are reported in Warren (1945). The committee examined Australian evidence, as well as evidence and arguments regarding similar proposals in other countries. The majority opinion regarding possible climate amelioration was that 'there may be improvement over strictly limited areas' in the vicinity of the water, 'but there appears no clear prospect of the enormous benefits to rainfall and climate envisaged by Dr Bradfield'. The committee further stated that 'The best that could be hoped for would be a slight amelioration of the climate, more particularly of temperature, in the immediate neighbourhood of the storage area'. Quayle, a member of the committee, submitted a dissenting report.

The Bradfield Scheme has been re-examined in Kotwicki (1986) and found to have many shortcomings. Most of these are due to assumptions about possible stream-flows based on limited data. When Kotwicki (1986) assessed the precipitation, evaporation and stream-flow data now available, along with data on the gradients of the rivers, the scheme was found to be flawed.

The following analysis concentrates on the rainfall response to a water expanse in the location of Lake Eyre. Although not all the schemes to increase water surfaces in inland Australia would necessarily mean permanent filling of Lake Eyre, it is probably the scheme that would cover the largest surface area with water. If the response to filling the immense expanse of Lake Eyre (or larger surrounding areas) produces a strong large-scale rainfall response, this result would likely apply to most schemes.

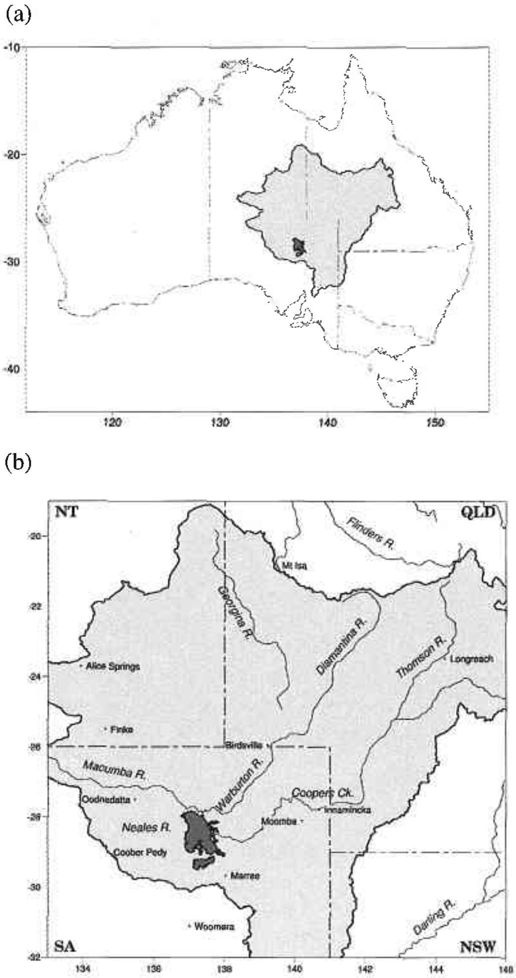
Description of Lake Eyre

Lake Eyre is a huge shallow salt lake in central Australia that is sometimes dry. It drains a catchment of 450 000 km^2, as shown in Fig. 1(a), approximately a sixth of the Australian land mass, and is the fourth largest internal basin in the world. Lake Eyre consists of two lakes - Lake Eyre North and Lake Eyre South, linked by the Goyder Channel. The total lake covers 9500 km^2, and when it is full its deepest point is only 6 m deep, and approximately 15 m below sea level (Bye et al. 1978). The bathymetry changes during and after a filling due to the solution and re-deposition of the surface salts. Figure 1(b) shows the catchment, Lake Eyre North and South (shaded dark), and some of the surrounding rivers and towns.

The majority of inflow to Lake Eyre is from the rivers to the north which include the Georgina, Diamantina, Warburton and Cooper. The combined catchment area of these rivers is 365 000 km^2, providing an annual average flow of 2.4 km^3 (Kotwicki 1986). Water from the Georgina and Diamantina rivers flows into Lake Eyre every second year or so, while flow from other sources is more sporadic. West and south, the rivers include the Macumba, Neales, Frome, Margaret and Warriner, with a mean annual input of 0.74 km^3. The water in the rivers that feed into Lake Eyre is often lost to evaporation and infiltration into the flood-plains and dunes well before it reaches the lake (Knighton and Nanson 1996). For instance the rivers to the northwest, including the Hay, Plenty and Finke, traverse and usually end in the Simpson Desert and rarely reach Lake Eyre.

Early recordings of the fillings of Lake Eyre date from Edward John Eyre in 1840, but have been sporadic since then due to the limited population surrounding the lake. The first verified extensive flooding of Lake Eyre was in 1949 (Bonython and Mason 1953; Peake-Jones 1955; Allan 1985). There can be problems with the quality of the evidence of Lake Eyre filling. Because of the shallowness of the lake, if it is only partially full (as in 2000) no water may be in sight from the edge if the wind is blowing away from

Fig. 1 **(a) Location of Lake Eyre (dark grey) and its catchment (light grey), (b) the catchment, Lake Eyre North and South (shaded dark), and some of the surrounding rivers and towns.**



the shore. An increased number of flights in the region have increased the number of sightings of fillings in the second half of the 20th century, although there are limitations with estimates of the extent and depth of the filling from the air, since extremely shallow water can give the appearance of a great deal of water (http://lakeeyreyc.com). Satellites have provided a basis for quantitative values of the extent of fillings. Fillings, estimated from satellite data, ground observations and hydrological models are shown in Fig. 2. The annual data (top panel) are from Allan et al. (2001) and Allan (personal communication 2003) and represents the inflows. Depth data derived from satellite images, confirmed by ground observations,

Fig. 2 Top panel is the annual volume inflow to Lake Eyre, data from Allan et al. (2001) and Allan (personal communication 2003). Bottom panel is the estimated monthly volume of Lake Eyre South and basins in the south of Lake Eyre North, in km^3.

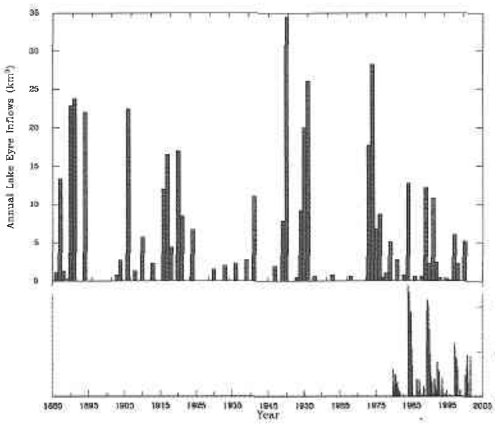
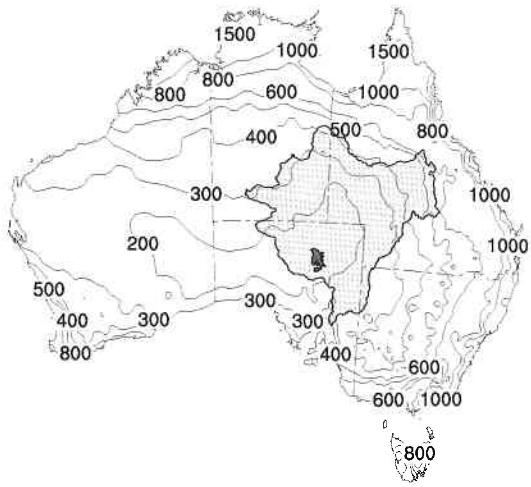


Fig. 3 Average annual rainfall (mm) 1960-90. Eyre catchment is shaded light grey, and Lake Eyre is shaded dark.



from Bob Backway (personal communication 2003) have been converted to monthly volume data, shown in the bottom panel of Fig. 2.

The largest known filling since European settlement was in 1974 to 1976, described extensively, with many references, in the book of Bonythen and Fraser (1989). The event aroused so much interest that there are many photographs available to document the extent of the filling, although the level posts in Level Post Bay were washed away (Dulhunty1989).

Evidence over the last 50 years indicates that portions of the lake partially fill every three years or so, that the lake floor is completely covered about every 8 years with major floods about every 20 years, and that Lake Eyre is rarely completely dry. The monthly volume estimates in Fig. 2 illustrate this well. The fact that Lake Eyre often has some water in it means that the current climate is already modified by the presence of water in Lake Eyre.

Climate

Lake Eyre and much of its catchment is located in the driest part of Australia, with the average rainfall for the whole catchment at about 250 mm per year (see Fig. 3). Gentilli (1971) describes the air mass over much of the catchment as being all of continental origin in both summer and winter. The northeast of the catchment receives the largest rainfall amounts, mostly associated with the summer monsoon (Gentilli 1971). The rest of the catchment is at the geographical extremes of the extent of systems associated with the monsoon to the north and the westerlies to the south. Rainfall is generally associated with sporadic large-scale events.

Lake Eyre can flood via rainfall from different types of systems. The meteorological conditions associated with the floods of 1949, 1955, 1974 and 1976 were a large-scale modification of the monsoonal flow, causing heavy rains in the catchment to the northeast of Lake Eyre (Allan 1985). The 1984 flooding resulted from a quite different situation, with persistent rain from a transient system passing over the western portion of the catchment, particularly the feeders to Lake Eyre South (Allan et al. 1986). This storm was very effective in filling Lake Eyre since rainfall in the local area of the lake suffers less transmission loss (Tetzlaff and Bye 1978).

Potential and pan evaporation in the region of Lake Eyre is high: at Birdsville the mean annual pan evaporation is 3358 mm, whereas the rainfall is 169 mm. A reduction in the potential and pan evaporation has been noted when Lake Eyre is full. Evaporation was estimated at 2000 mm yr^{-1} off the full lake for the years 1951 and 1975 (Bonython and Mason 1953; Tetzlaff and Bye 1978). When Lake Eyre was full in 1974 the pan evaporation at nearby stations reduced to 1800 mm yr^{-1} (Tetzlaff and Bye 1978), but, assuming that pan evaporation provides a reasonable estimate of the potential evaporation, it is still much greater than the rainfall. With this potential for high levels of evaporation, to maintain a full lake would require an enormous increase in both the volume and consistency of the inflow. Kotwicki (1986) estimated that to offset the evaporation alone, 18.9 km^3 yr^{-1} inflow would be required, about six times the current average annual inflow, and equivalent to the annual discharge of the Murray River, (http://lakeeyreyc.com), or three days of Amazon discharge, or the volume of an Olympic swimming pool every four seconds for a whole year.

High rainfalls in the catchment have a close association with the El Niño-Southern Oscillation (ENSO) phenomenon, with increased rainfall during La Niña events – when the Southern Oscillation Index (SOI) is high. The correlation coefficient between annual (May-April) SOI and the rainfall in the Eyre catchment is high, 0.45 (significant at the 99 per cent level) for the period 1925-1990. Corresponding with the strong link between rainfall and the SOI, Allan et al. (2001) show a significant correlation between Lake Eyre inflows and the SOI of 0.37 for the years 1885-2000. This correlation varies with time, and Allan et al. (2001) link these variations to decadal climate variability. Any influence that the lake being full has on distant rainfall would likely be dominated by the large-scale influence of ENSO.

Response to surface water in other countries

The 1945 inquiry into the Bradfield Scheme Warren (1945) reviewed the international literature available at that time on the possible impacts of increases of inland water storages and irrigation on climate. The inquiry concluded that 'in no case did the references establish evidence of material influence on rainfall or climate in the areas of the inland water storages and irrigation areas'. More recent studies of the possible climatic influence of large-scale surface change for quite different climate regimes around the globe have now been assessed.

The USA has seen an extensive increase in irrigation over the last century. A statistical study of the conditions in central USA by Barnston and Schickedanz (1984), extending an earlier study by Schickedanz (1976), suggested that irrigation enhanced rainfall from naturally occurring systems. Thus stationary fronts, that entrain surface moisture as they persist over the region, resulted in rainfall from the irrigated surfaces. The overall climatic response to irrigation was decreased temperature, particularly during the day, and increased vapour content. These changes were evident at stations up to 160 km from the main irrigated regions. Moore and Rojstaczer (2001), examining the same region, found that for the period 1950-97 there is 'at best, slight evidence that irrigation induces rainfall' and that 'If irrigation-induced rainfall exists, its impact is only minor relative to the natural determining factors of plains climate'. Moore and Rojstaczer (2001) also suggested that the apparent irrigation effects noted by Barnston and Schickedanz (1984) may simply have been due to a large-scale increase in precipitation rather than an irrigation effect.

The USA rainfall response to irrigation was further considered from both a conceptual viewpoint and using a mesoscale model by Segal et al. (1998). In their conceptual model they suggested that moisture evaporated from irrigated areas in dry regions may act as a source for rainfall downwind. With a dynamical mesoscale model they assessed normal, drought and flood conditions with irrigated and non-irrigated surfaces. They found that irrigation did indeed alter existing rainfall regions but concluded that 'the impacts of irrigation on the resolvable rainfall systems were generally so weak that hardly any new rainfall areas were generated; rather, irrigation only altered existing rainfall fields'.

In West Bengal, India, a westward shift in rainfall and storms has been noted by Singh and Sontakke (2002) who suggested this shift was probably due to large-scale circulation changes, rather than associated with changes in irrigation. They did, however, suggest that 'A combined effect of regional (expansion and intensification of agricultural activities and spreading irrigation network) and global environmental changes... appears to be the main cause of cooling' in the region from 1958.

Increases in irrigation in the south of Israel since the mid-1960s have coincided with increased annual rainfall, discernible decreases in the diurnal temperature range and an increase in early wet season convective rainfall. Such changes were reproduced in a simple model experiment of de Ridder and Gallee (1998) leading to the conclusion that irrigation could lead to enhanced moist convection. Ben-Gai et al. (1994) agree that the increased irrigation may have contributed to the observed increase in annual rainfall totals for 1961-1990, though they also suggested that the early 1960s was a time when the global sea-surface temperatures were changing, affecting large-scale systems. Steinberger and Gazit-Yaari (1996) agreed that the change in Israeli rainfall was related to large-scale circulation changes, and discounted possible influences from irrigation changes. They pointed out that rainfall had actually decreased in the northern parts of Israel.

In each of the cases mentioned above, increased irrigation leads to a local decrease in temperature and sometimes changes in precipitation (although the evidence regarding the precipitation effect is less clear). Any increases in rainfall tend to occur in regions where there was rainfall prior to the irrigation. Responses distant to the moisture source are not as clear as those in the local region. Thus the evidence from international studies suggests that maintaining a constantly full Lake Eyre might reduce temperatures locally, and perhaps modify convective storms in the Lake Eyre region. The international studies do not provide evidence that a constantly full Lake Eyre, or extensive irrigation, would result in major, widespread increases in precipitation distant from the water surfaces.

Land-atmosphere interaction

The question of whether a full Lake Eyre will increase the moisture available for precipitation can be addressed by examining a measure of the strength of the interaction between the land surface and the atmosphere. One such measure is the moisture recycling, which is the ratio of the rainfall derived from evaporation arising from a target region to the total precipitation over that region. The numerical value of the recycling ratio is dependent on area, and will go to zero as the area goes to zero, and towards unity as the area becomes large.

Eltahir and Bras (1996) provide an overview of some of the methods used to calculate the recycling ratio. There are a number of assumptions and limitations. The assumptions include that the moisture in the air is well mixed, the storage of water vapour is small compared with the fluxes and that the flow is close to linear (Burde and Zangvil 2001). The major limitation is the veracity of the moisture fields in reanalyses (Trenberth and Guillemot 1995).

An equation for moisture recycling balancing the incoming moisture, the local actual evaporation and the area is presented by Brubaker et al. (1993). They assessed the degree of moisture recycling over four regions of the globe and found that in general there is high seasonal variability with greater recycling in summer. The particular characteristics of each region are important to the potential for the recycling of locally derived moisture. An area with a strong mechanism for precipitation would result in precipitation of most of the moisture present, leading to strong recycling, while an area of stable air would have less potential for moisture recycling.

To assess the degree of land-atmosphere interaction the moisture recycling ratio as defined in Brubaker et al. (1993) was calculated using NCEP/DOE Reanalyses II data for the Eyre catchment. The moisture recycling ratio over the region is highest in summer and autumn, and very low in winter. This is consistent with the maps of recycling ratio in Trenberth (1999). The correlation between the seasonal rainfall for the Eyre catchment and the time-series of the recycling ratio over the same region for the period 1980-2000 is significant and positive, indicating that the higher the rainfall, the greater the amount of moisture recycling. The correlation between seasonal rainfall and the estimated volume of Lake Eyre, as shown in Fig. 2, is also positive and significant at zero lag and when the rainfall leads by one season. The correlation between the volume of water in Lake Eyre and the moisture recycling is zero, with no significant correlations at any lag in any season, indicating that a full Lake Eyre has no influence on the recycling of moisture across the Eyre catchment. The maps of moisture recycling of Trenberth (1999) show the majority of the moisture recycling is in the northeast of the Eyre catchment, with very little over Lake Eyre itself in any season. These results indicate the small influence that water in Lake Eyre has on the amount of subsequent rainfall in the region.

Model response to a full lake

Large salt lakes produce a mesoscale response in the local environment when they are dry (Physick and Tapper 1990) and wet (Yan and Anthes 1988). Once the wet surface of a lake is wider than 96 km (approximately the width of Lake Eyre) Yan and Anthes (1988) found that a simple numerical model with moist physics produces rainfall 69 km away from the edge of the lake. These results indicate that the presence of an inland water expanse modifies the local environment, but to assess the continental response, larger-scale models are required.

To test how an imposed water expanse in the approximate location of Lake Eyre would alter Australia's rainfall, an inland lake was represented in a number of ways in two global atmospheric models. These are the variable-resolution version of the CSIRO conformal cubic atmospheric model (C-CAM) and the Melbourne University atmospheric general circulation model (MUGCM).

Model description

The resolution of C-CAM used here is 65 km over Australia, extending to 800 km on the other side of the globe. The model is described in McGregor and Dix (2001). The model physics include six layers for soil temperature and moisture as described in Gordon et al. (2002) and the model has prescribed vegetation and soil types. The far-field winds are prescribed and their influence reduces to zero approximately 2000 km from the Australian coast. The convection is modelled with a mass-flux cumulus scheme described in McGregor (2003). In the simulation termed C-CAMa the shallow convection is considered as part of the deep convection, while in C-CAMb a modified version of Tiedtke's (1984) method is used. C-CAMa has the initial conditions, sea surface temperatures (SSTs) and far-field winds prescribed from NCEP/NCAR (National Center for Atmospheric Research) reanalyses (Kalnay et al. 1996) for the years 1979 to 1989, with the first year discarded to allow spin-up. The output from the CSIRO Mk3 coupled general circulation model (Gordon et al. 2002) with greenhouse gas levels corresponding to the years 1980 to 1989 is used to force C-CAMb.

The MUGCM is a spectral model based on the model described by McAvaney et al. (1978). Noone and Simmonds (2002) describe further developments in the physics and parametrisations. The land surface has no vegetation, a two-layer soil moisture scheme (Hunt 1985), and albedo is calculated dependent on the soil moisture (Laval and Picon 1986). Convection is by adiabatic adjustment and the prognostic clouds are as described in Argete and Simmonds (1996). Unlike the version of the MUGCM described in Noone and Simmonds (2002), the moisture transport in the version used here is spectral. MUGCM can be run at two resolutions, rhomboidally truncated at 21 (R21) and 31 (R31) waves. The R21 resolution is approximately 5.3° longitude by 3.3° latitude, while R31 is 3.7° by 2.2°. Monthly climatological SSTs are prescribed from Reynolds (1988) for the years 1981-85.

The precipitation in the control simulations for C-CAMa and b and MUGCM R21 and R31 are within the range of variability shown between general circulation models, (e.g. Zhang et al. (2002)). Comparison of the model results with the high-quality Australian gridded rainfall (Jones and Weymouth 1997) shows that C-CAMa simulates Australian rainfall particularly well with only very small areas having errors greater than 50 mm month^{-1}. C-CAMb produces a similar pattern of precipitation anomalies to C-CAMa, though it is wetter, while MUGCM has negative precipitation errors in the west with consistent positive errors elsewhere.

Defining the lake

Representing lakes in a GCM can be quite complex (e.g. Bonan (1995)) but a large, shallow lake such as Lake Eyre does not present some of the usual problems. Full grid-points can be used and the depth of the simulated lake and its associated thermal inertia do not need to be considered. In C-CAMa and b, the lake is defined with permanently wet soil moisture over rectangular areas equivalent to Lake Eyre and Lake Torrens (to the south). The roughness length over the lakes is set to 6 cm.

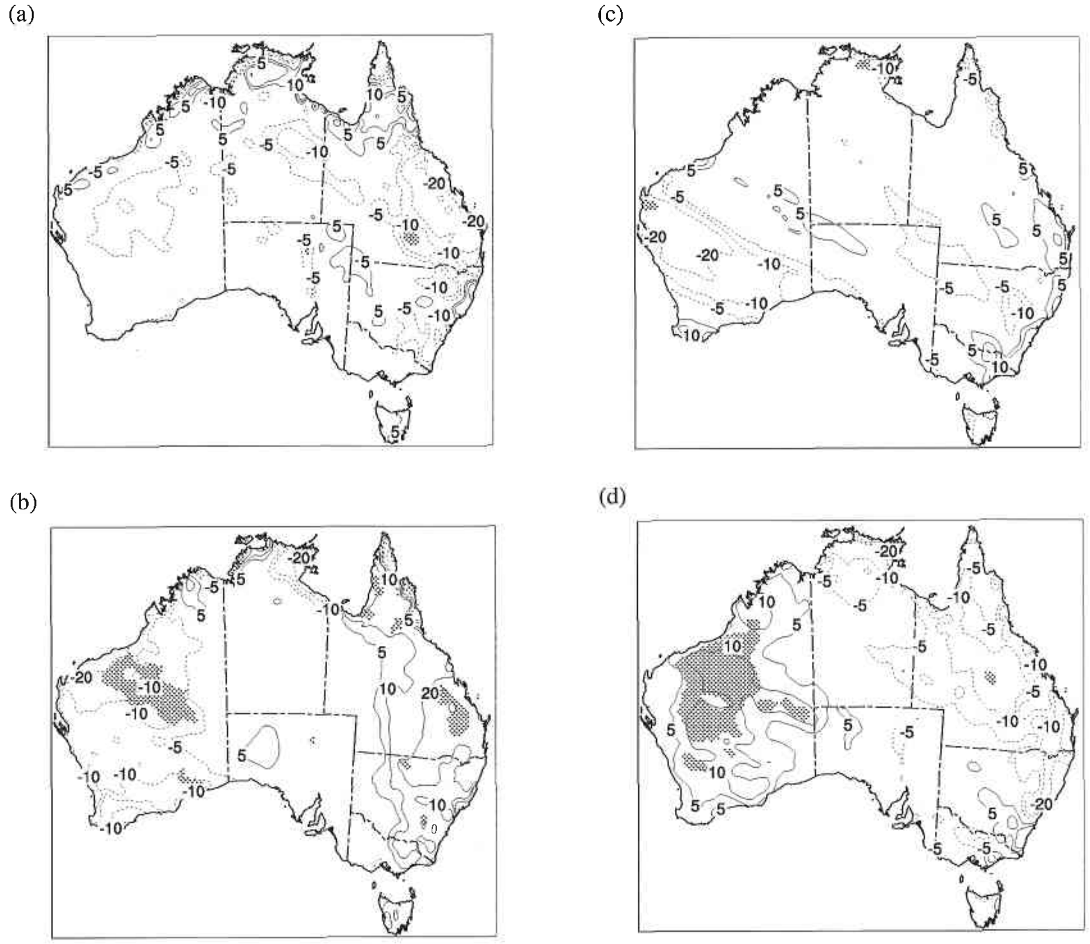
The roughness length in the MUGCM is set to 29 cm over land. Setting a full grid-point to saturated soil in the region of Lake Eyre results in a strong increase in the latent heat flux and a reduction in temperature. For typical values of temperature, wind and humidity, this roughness length results in 2.6 times more latent heat flux than with a typical roughness length over a water surface. This was calculated from the evaporation equation in MUGCM (Simmonds1985) and from experiments using the roughness lengths for land and water. Thus to best simulate a lake, the grid-point(s) in the location of Lake Eyre are represented by permanently saturated soil with drag calculated as if over water. The method reduces the extreme latent heat flux that results when the MUGCM standard roughness length for land is used. The response in the MUGCM with reduced lake roughness length is less than in C-CAMa or b, perhaps indicating that the 6 cm roughness length specified in C-CAMa and b is too large, exaggerating the response.

Results

The strongest response for both C-CAMa and b in the Lake Eyre region is a large increase in the latent heat flux and an associated surface air cooling. The potential evaporation is decreased along with the decrease in temperature and the increased humidity. The changes are largest in summer and accompanying the cooling there is a strong decrease in the local precipitation, by more than 70 per cent of the usual summer precipitation in C-CAMb.

Across the Australian continent away from Lake Eyre there are few regions with precipitation anomalies significant at the 95 per cent level in either C-CAMa or b. The significance of anomalies is calculated using the method of Chervin and Schneider (1976), based on the Student t-test. Figure 4 shows the seasonal precipitation anomalies from C-CAMa with differences significant at the 95 per cent level stippled. There is a region of significant increase in Western Australia in spring (Fig. 4(d)), but the same area shows a decrease in the other three seasons. In summer and winter there are no regions of significant change anywhere across Australia.

Fig. 4 Rainfall anomalies for C-CAMa for each season, (a) summer (DJF), (b) autumn (MAM), (c) winter (JJA) and (d) spring (SON). Contour intervals -20, -10, -5, 5, 10, 20 mm month^{-1}. Negative contours are dashed. Stippling indicates significant difference at the 95% level.



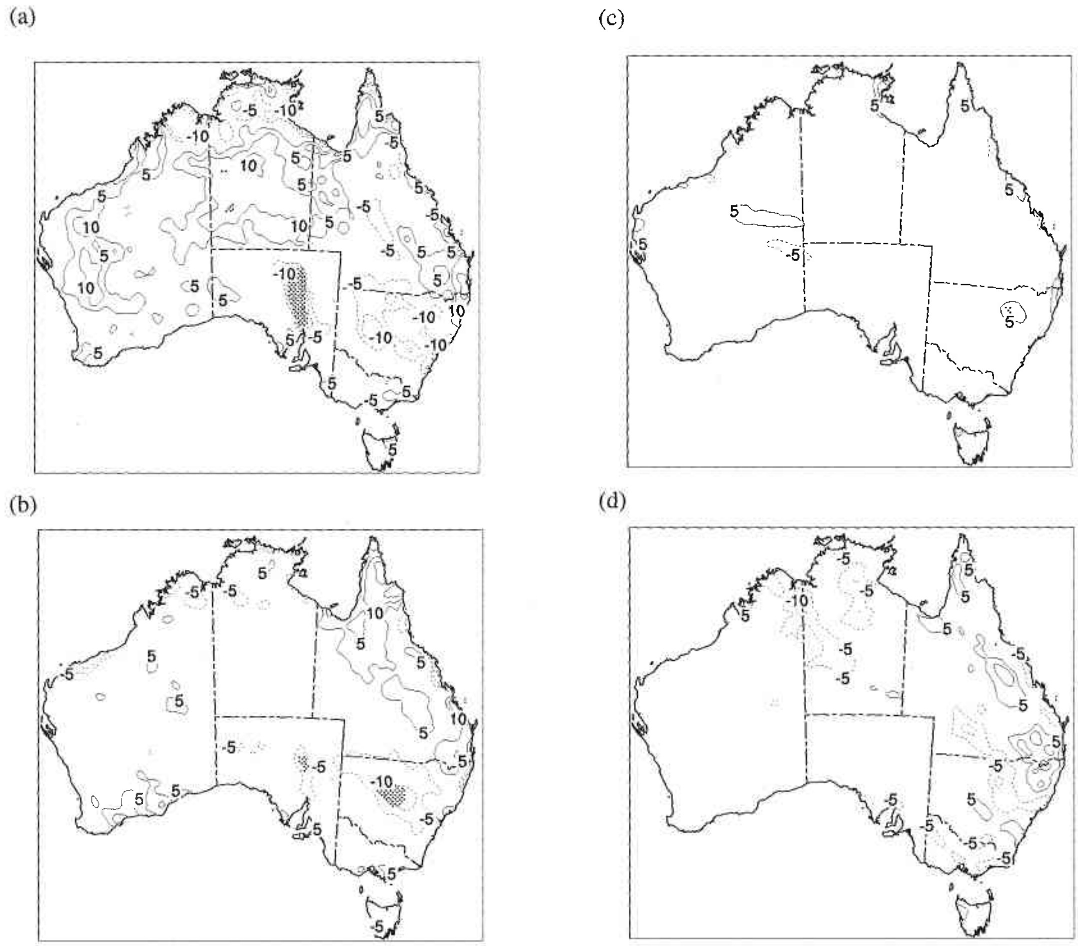
If the signal from filling Lake Eyre and Torrens was strong, the modest changes in convection and sea-surface temperature forcing between C-CAMa and C-CAMb should make little difference to the response. The seasonal precipitation anomalies for C-CAMb are shown in Fig. 5. The major result of note is, besides the decreased precipitation over Lake Eyre in summer, that there are no other regions with a consistent significant response.

Due to the lower resolution of the MUGCM, and the relatively short time needed to carry out simulations, several tests were performed to assess the sensitivity to differing lake surface parametrisations, model resolution and varying lake size.

The response in the MUGCM R21 experiment with a standard size lake shows small regions of significant change in precipitation at the 95 per cent level across Australia (not shown). Like C-CAMa there is a significant increase in precipitation in central Western Australia in spring, but only small regions of significant change in the other seasons. The MUGCM resolution has little bearing on the results, with the anomaly pattern for R31 being consistent with that for R21.

The model is sensitive to the size of the lake imposed. The extent of the broader reaches of Lake Eyre North and South is 100 by 200 km. The lake defined in the MUGCM is one grid-point in the R21, two in the R31, approximately 500 by 360 km. This is a good deal larger than the actual Lake Eyre, allowing any response to be amplified somewhat. To test the sensitivity to the size of the lake, an enormous lake of 720 by 750 km was imposed in the R31 simulation. This covers much of South

Fig. 5 **As for Fig. 4 but for C-CAMb.**



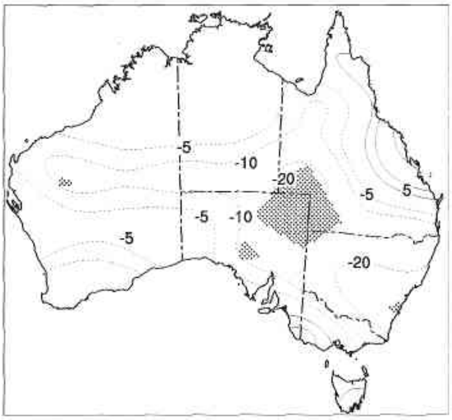
Australia. The response to this huge lake is a significant increase in rainfall by about 146 mm yr^{-1} over much of the lake and west into the Gibson Desert in central Western Australia. There are also large decreases in precipitation on the southern east coast. This result indicates that with a large enough area of Australia inundated, there will be a response in the precipitation, though not a universal increase.

To compare results with those of C-CAMa, the MUGCM was forced with varying observed SSTs from the Global Sea-Ice and Sea Surface Temperature (GISST) dataset provided by the British Atmospheric Data Centre (Rayner et al. 1996) for the years 1978 to 1989, with a spin-up of two years. To determine the level of consistency of the response in the model, five control and five Lake Eyre experiments were started from different times in early January 1978. The climatology of all of the control ensemble members was very similar, as were the Lake Eyre ensemble members, but the Lake Eyre minus control precipitation anomaly was not consistent at any place across the five. The difference between two of the ensemble member winter precipitation anomaly patterns shown in Fig. 6 indicates just how variable the response can be.

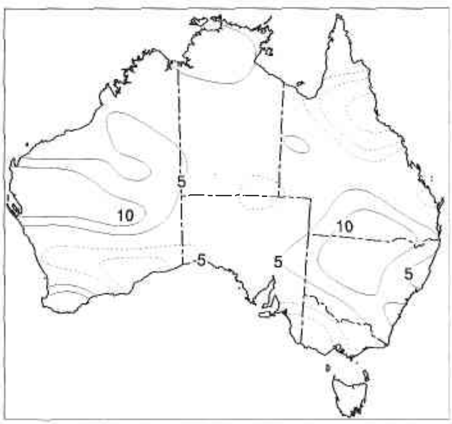
With a reasonable representation of Lake Eyre, the results from C-CAM and MUGCM show a slight local cooling and an increase in latent heat flux over the imposed lake. Away from the lake, the changes in precipitation are not consistent between the models nor between ensemble members and they are not significant. These results suggest that maintaining a full Lake Eyre is unlikely to modify Australia's rainfall in any consistent or significant way.

Fig. 6 Rainfall anomalies for two MUGCM ensemble members, (a) member 4 and (b) member 5, for winter. Contour intervals -20, -10, -5, 5, 10, 20 mm month^{-1}. Negative contours are dashed. Stippling indicates significant difference at the 95% level.

(a)



(b)



Conclusions

At first sight, it is an appealing idea that a massive increase in water surfaces in inland Australia would lead to increased rainfall over agricultural areas. There has been speculation for over a century that schemes to 'water the inland' might enhance agricultural productivity. The general conclusion of those who have studied such proposals, however, has been that they are unlikely to produce the massive benefits suggested by the proponents of the schemes. Our conclusion matches those of earlier assessments: although there seem likely to be local climate changes (cooling over the lake and nearby) none of the approaches we have used suggest that major, widespread rainfall increases are likely. This conclusion also seems consistent with related international studies.

The inland water expanse considered here has been in the region of Lake Eyre, the filling of which is a common suggestion in many of the schemes. One observation that will modify how a large inland lake will ameliorate the climate is the fact that Lake Eyre is actually rarely dry, and so the current conditions may not be far removed from those produced when its whole extent is constantly wet. ENSO influences will also likely swamp any influence of a full lake on rainfall in eastern Australia. The moisture recycling in the catchment is predominantly in the northeast and is linked to rainfall but has no correlation with the filling of Lake Eyre. The results from imposing an inland water expanse in Australia in global atmospheric models show that given a large enough lake, there will be a precipitation response. But, for water stretches less expansive than the size of South Australia, the precipitation response away from the lake is unclear and variable.

We recognise that each of the approaches we have used has its deficiencies. If we were looking for a subtle change in rainfall these deficiencies might be important. However, we are attempting to determine if an inland water surface leads to a major, widespread increase in rainfall. Only if this were the case could it be economically viable to undertake a scheme to flood the inland. Despite their deficiencies, the approaches we have used should be able to detect such a large effect. Since none of the approaches suggest that such a large, widespread effect is likely, it seems reasonable to conclude, as did Warren (1945), that any change would be minimal and unpredictable.

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