Evidence of impacts from rising temperature on inflows to the Murray-Darling Basin

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[1] The 2001–2007 Australian drought was the hottest on record with inflows to Australia's longest river system, the Murray-Darling, reaching an historical low. Here we examine the relative importance of rising temperature and decreasing rainfall over its catchment, the Murray Darling Basin (MDB). Although annual-total inflow is more sensitive to rainfall over the southern MDB, where rainfall since 2001, has been the lowest on record, this alone can not explain the observed inflow decline. A relationship exists between inflow variations and fluctuations of temperature not associated with rainfall in the austral winter and spring: a rise of 1°C leads to an approximate 15% reduction in the climatological annual inflow. Our results provide strong evidence that rising temperatures due to the enhanced greenhouse effect have a strong impact on southern Australia's water resources, in addition to any reduction in rainfall, and project a long-term decline in inflows to this river system as the greenhouse effect continues. **Citation:** Cai, W., and T. Cowan (2008), Evidence of impacts from rising temperature on inflows to the Murray-Darling Basin, *Geophys. Res. Lett.*, *35*, L07701, doi:10.1029/2008GL033390.

1. Introduction

[2] Located in south-eastern Australia, the MDB encompasses the catchment areas of the Murray and Darling Rivers and their many tributaries. The Murray-Darling is Australia's longest river system, covering an area of about 1.0 million square kilometres. It is a vital economic resource with one-third of Australia's total output for natural resource-based industries, worth approximately $14 billion per year, produced within the basin. The inflow into the Murray-Darling river system has a long term post-1950 average of over 12,300 GL yr^{-1} (1 GL = 10^9 litres) (see Figure 1a).

[3] The inflow, however, experiences significant fluctuations on interannual to multi-decadal time scales. During the Federation drought (1895–1902) [*Watkins*, 2005] the average annual inflow was only 5400 GL yr^{-1}. A previous 12-month minimum was recorded during 1914–1915 at 1920 GL yr^{-1}. During the present drought (2000–2007), the average annual inflow is 4150 GL yr^{-1}. In 2006–2007, the 12-month inflow reached a new low of 770 GL yr^{-1} ending in March 2007. The six-year total rainfall over the MDB from November 2001 to October 2007 was the equal-driest six-year period on record, which occurred during 1939–1945 at 389 mm year^{-1} (Figure 1b). One difference is that the recent drought is hotter. Already, there are suggestions that the anomalously high temperatures recorded in recent years have exacerbated the impacts of the recent drought [e.g., *Nicholls*, 2004]. Here we assess the potential importance of rising temperature in generating the decreasing MDB inflow, and discuss the relative importance of rising temperature and decreasing rainfall.

2. Data and Method

[4] A time series of monthly total inflow to the river system since 1900 is provided by the MDB Commission, an Australian government management agency. The inflows include those from rivers such as the Murrumbidgee, Goulburn, Campaspe, Loddon, Kiewa, Ovens, Hume, and Dartmouth, as well as the Darling, adjusted through hydrological computer models of these systems for current conditions of development. In this way, the inflows have taken into account long-term changes in human activities, such as extractions and landscape changes, although some uncertainty may still exist arising from farm dams and catchments changes.

[5] Monthly rainfall averaged over the MDB, monthly climatological mean areal potential evaporation, gridded monthly rainfall and temperature, are provided by the Australian Bureau of Meteorology (BoM). For monthly temperature (monthly average of daily maximum temperature (Tmax) and daily minimum temperature (Tmin)), the data start from 1950. To elucidate the impact of temperature, seasonal stratification is necessary, and as Australia experienced little warming prior to 1950 we therefore focus on the period since 1950. Raw data and anomalies referenced to the 1950–2006 climatology are used. Most of the inflow is generated in the austral winter and spring (Figure 1c), when basin-wide areal evaporation is low (Figure 1c) and the southern MDB (30°S southward, e.g., Victoria) rainfall is strong (Figure 1d).

[6] Fluctuations of rainfall and temperature are not independent [*Nicholls et al.*, 1996; *Jones and Trewin*, 2000], as rainfall events lower daily maximum temperature. One objective is to establish a relationship between inflow and the component of temperature fluctuations that is not related to rainfall variations, hereafter referred to as the residual temperature. Following the partial regression/correlation approach of *Nicholls* [2004], we regress time series of temperature onto raw rainfall time series for each individual month. This gives temperature variability that is related to rainfall, which is then subtracted from the raw temperature. Similarly, we establish monthly residual inflow for each month, after removing inflow anomalies associated with monthly rainfall. Thereafter, the data are linearly detrended, so that the relationship is not influenced by any trends in both time series.

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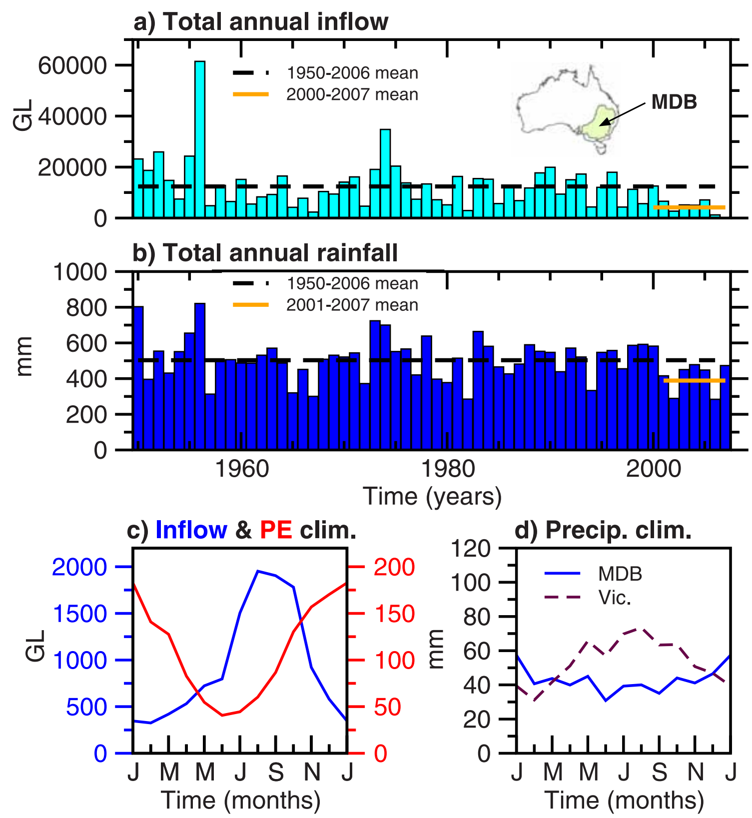

Figure 1. (a) Time series of annual-total inflow to the MDB, with an insert showing the region of interest (light green area) and (b) annual-total rainfall averaged over the MDB (see inset). Annual cycle of (c) inflow (blue line) and areal potential evaporation (red line), and (d) rainfall over the MDB (solid line) and Victoria (dashed line). Superimposed on Figures 1a and 1b are long (dashed black line) and short-term (solid orange line) averages.

[7] In 1956, the annual inflow was about five times as large as the long-term average. As will be clear, inflow to the MDB decreases as residual Tmax increases. An analysis reveals that including this year enhances this sensitivity, and hence increases the impact of rising temperature. To avoid distortion from this outlier, we exclude 1956 from our analysis although we still display the year in Figure 1. Without 1956, the multidecadal decline in inflow since 1950, obtained from a linear trend analysis, is 7112 GL.

3. The Relationship Between MDB Inflow and Climate Variables

[8] The relationship between anomalies of annual-total inflow and rainfall averaged over the MDB is strong with a correlation of 0.71 (Figure 2a). An increase of 1 mm in annual-total rainfall is associated with an increase of 42 GL in annual-total inflow, i.e., the "conversion rate" is 42 GL mm^{-1}, which is mainly carried out in the austral winter and spring seasons. As will be discussed later, although the conversion rate in austral autumn *per se* is low, rainfall in this season is important for annual-total inflow (Figure 2b).

3.1. Coherence of Inflow With Climate Anomalies

[9] The analysis in Figure 2 reduces the MDB to a "bucket." To obtain the spatial structure and the seasonal stratification of the contribution from rainfall and temperature, we conduct a correlation analysis between annual-total inflow and grid-point seasonal mean rainfall, and between anomalies of residual seasonal total inflow and residual seasonal mean Tmax and Tmin (Figure 3).

[10] Several features emerge. Firstly, in autumn (March-April-May, MAM), winter (June-July-August, JJA) and spring (September-October-November, SON), southern MDB rainfall anomalies are more coherent with inflow than the northern regions of the basin. The high correlation in MAM is worth mentioning. It means that good rainfall is important for the annual-total inflow (Figure 3b). Regressing annual-total inflow anomalies onto MAM rainfall yields a conversion rate of 55 GL mm^{-1} (Figure 2b), which is greater than the annual-mean rate. By contrast, the conversion rate within MAM is low (see section 3.2) indicating a soil "wetting mechanism" by autumn rain with delayed impacts on the proceeding seasons. We emphasize this feature because MDB rainfall experiences a greatest reduction in MAM. In section 4, we show that this seasonality of rainfall reduction is not a catalyst for the unprecedented inflow decline.

[11] Secondly, in JJA and SON, the correlation between residual seasonal-total inflow and residual seasonal-mean Tmax (Figures 3e–3h) is large and statistically significant in most regions of the MDB: a higher Tmax is associated with a lower inflow. This constitutes supporting evidence for an impact from rising temperature on inflows. The

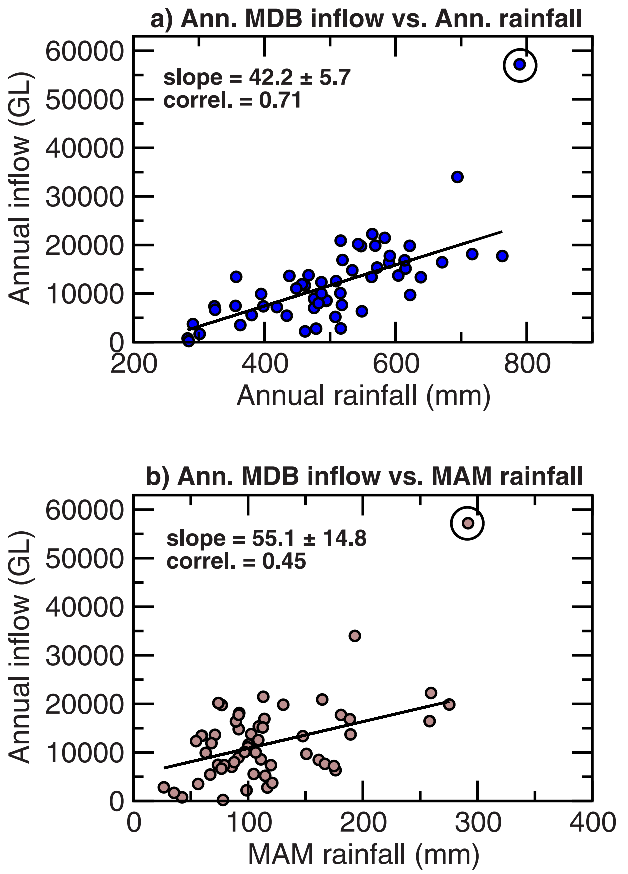

Figure 2. (a) Scatter diagram of annual-total MDB rainfall versus annual-total inflow to the Murray Darling River System. (b) Scatter diagram of MAM MDB rainfall versus annual-total inflow to the Murray Darling River System. All data are linearly detrended, and the analysis is carried out without 1956 data (circled). A correlation greater than 0.27 is significant at the 95% confidence level.

correlations in December-January-February (DJF) and MAM are weak, and less spatially uniform over the MDB.

[12] Finally, the relationship between residual seasonal-total inflow and residual Tmin is generally weaker than that with residual Tmax, particularly in JJA and SON, when the impacts of rising temperature occurs (see section 3.2). A higher rainfall (hence a higher inflow) can sometimes lead to an increase in Tmin, as the associated increase in cloudiness reduces the heat loss to space during night time. Since the correlation pattern with Tmax is better defined and has a stronger spatial coherence over the MDB, we will only use Tmax for the remainder of our analysis.

3.2. Sensitivity of Inflow to Rainfall and Tmax

[13] Despite the high coherence of MAM rainfall with annual inflow, the rate of conversion from rainfall anomalies to inflow anomalies in MAM, derived from a regression analysis using monthly data within the season (3×56 months), is low at 6.3 GL mm^{-1} (Figure 4b), with a correlation statistically insignificant. Thus, anomalous rain water, after evaporative loss, goes to soak the soil so that the conversion rate is enhanced in the proceeding seasons, leading to a larger annual conversion rate (Figure 2b). The MAM conversion rate is about one tenth of that in JJA and SON (Figures 4c and 4d), while the conversion rate in DJF is negligible (Figure 4a). We note that inflow/rainfall relationships are also subject to rainfall duration and intensity, which can be more accurately resolved at a daily time interval. However, only monthly data are available.

[14] The sensitivity of residual inflow to residual Tmax (Figures 4e–4h) in JJA and SON is statistically significant, at 319 GL °C^{-1} per month and 306 GL °C^{-1} per month, respectively, totalling to 1875 GL °C^{-1} for the two seasons. These results suggest a sensitivity of an approximate 15% reduction of the climatological inflow per 1°C rise.

4. Observed MDB Inflow Fluctuations Since 1950

[15] The extent to which the observed inflow fluctuations, which show a reduction of 7112 GL since 1950 using a linear trend analysis, is attributable to variability or climate change is beyond the scope of this study. Our analysis above suggests that annual MDB inflow variability can be described as a function of annual rainfall and residual Tmax in JJA and SON. Below we use these relationships to assess the relative importance of changing rainfall and rising Tmax in driving the multidecadal inflow reduction since 1950.

4.1. Contribution From the Rainfall Reduction

[16] Since 1950, the annual-total rainfall over the MDB (Figure 1b) has decreased by about 56 mm using a linear regression. Using this value and the relationship in Figure 2a, the rainfall decline contributes to 2368 GL, or about 33% of the observed inflow reduction since 1950.

[17] We also investigate the possibility that the rainfall contribution might be larger due to temporally and spatially non-uniform rainfall reductions over the MDB. For example, rainfall reduction since 1950 over the southern MDB (e.g., Victoria) is greater than that over the MDB as a whole in MAM, JJA, and SON, particularly in MAM. Figures 3a–3d show that inflow is sensitive to southern MDB rainfall, with MAM rainfall particularly important (Figure 2b). Will these non-uniform features lead to a larger contribution from rainfall? To address this issue, we calculate the Victoria rainfall reduction since 1950 for each season, and assume that the Victoria rainfall reduction is experienced throughout the entire MDB. Using the conversion rates in Figures 4a–4d, we find that such an exaggerated impact would only contribute to 3616 GL, or less than 51% of the observed total inflow reduction. We conclude that rainfall alone is unable to explain the post-1950 multidecadal inflow reduction.

4.2. Contribution From the Temperature Increase

[18] An analysis shows that since 1950, residual Tmax has increased by 0.94°C in JJA and 1.02°C in SON. The increase is at least in part due to greenhouse warming [*Nicholls et al.*, 1996; *Nicholls*, 2003]. Following the inflow-Tmax relationship (Figures 4g–4h), this would contribute to 993 GL residual inflow in JJA, and 936 GL residual inflow in SON. Their sum, 1929 GL, accounts for

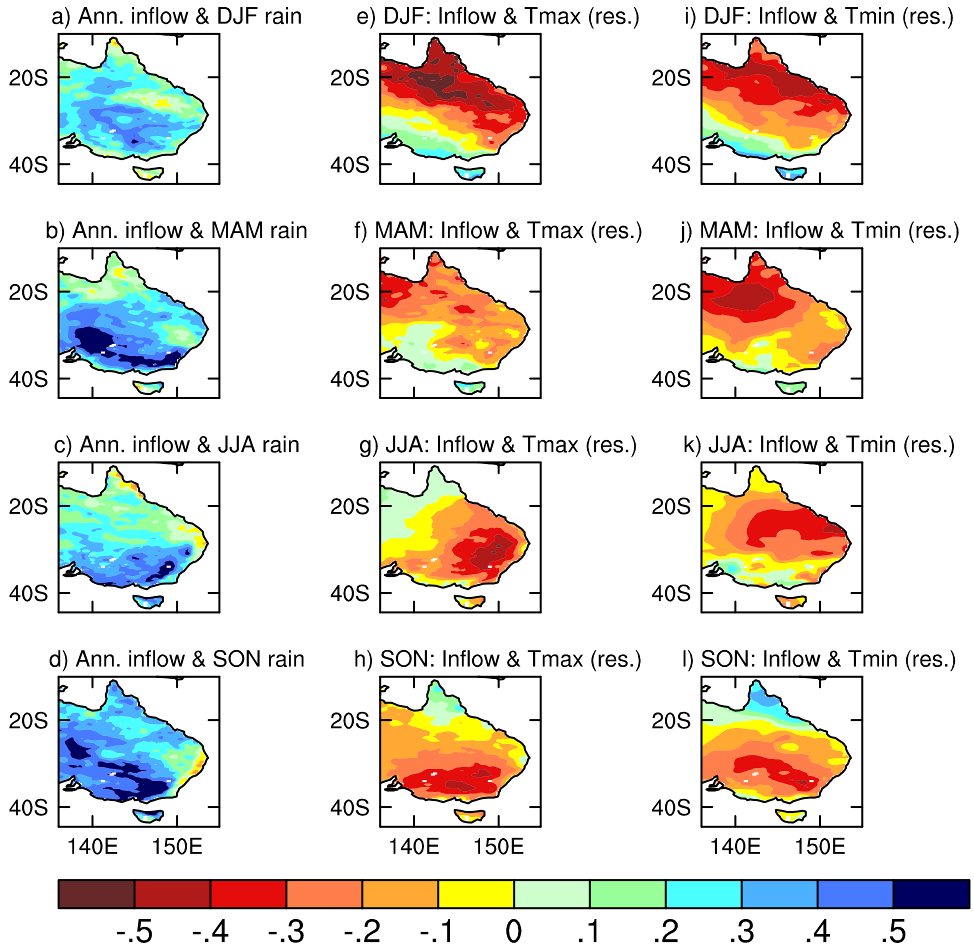

Figure 3. Maps of correlations between MDB annual-total inflow and seasonal rainfall (a–d), between residual seasonal-total inflow and residual seasonal-mean Tmax (e–h), and between residual seasonal-total inflow and residual seasonal-mean Tmin (i–l). All data are linearly detrended, and the analysis is carried out without 1956 data.

about 27% of the total inflow reduction, comparable to the rainfall component.

5. What Does the Future Hold for Inflows to the MDB?

[19] The future of MDB inflow depends upon the future rainfall and temperature changes. Climate change signals and impacts tend to project onto modes of interannual variability [*Shi et al.*, 2008]. Two known large-scale climate drivers affecting rainfall variability over the MDB are the Indian Ocean Dipole (IOD) [*Saji et al.*, 1999; *Cai et al.*, 2005] and El Niño - Southern Oscillation (ENSO) [*Nicholls et al.*, 1996]. The impact of ENSO occurs mainly in JJA and SON with anomalously low rainfall over the MDB during an El Niño event; the IOD mainly influences SON rainfall such that when the sea surface temperature (SST) in the eastern pole is anomalously low, MDB rainfall decreases. A correlation of SSTs and MDB rainfall with inflow for each season (not shown) clearly shows these influences.

[20] Climate models project a median annual rainfall reduction of 5–15% by 2060 over the MDB [*Christensen et al.*, 2007]. The consensus is strong because the reduction is mostly in JJA and SON, in which the warming pattern in the eastern Indian Ocean is IOD-like, due to a robust greater transient greenhouse warming of the Eurasian landmass than that over the ocean [*Ashrit et al.*, 2001, *Hu et al.*, 2000, *Shi et al.*, 2008]. If we assume that the relationship shown in Figure 2a is valid in a future climate, then a 15% rainfall decrease (about 75 mm) would contribute to a 3150 GL reduction by 2060, or about 25% of the present-day climatological value.

[21] If the relationship between Tmax and inflow in JJA and SON (Figures 4g–4h) persists into a future climate, a 2°C increase by 2060 (the mid-range A1B scenario) will reduce the inflow by 1914 GL in JJA and by 1836 GL in SON, totalling 3750 GL, or about 30% of the present-day mean inflow, comparable to that due to a rainfall reduction. This will have significant implications. In the next 50 years, as the warming proceeds, this relationship may change, so detailed hydrological modelling is needed. With this in mind, however, our result does highlight how severely a 2°C rise in temperature due to the anthropogenic greenhouse effect could exacerbate the impact of a rainfall reduction on MDB inflow.

6. Conclusions

[22] Our analysis reinforces the notion that a rainfall reduction alone is unable to explain the observed inflow

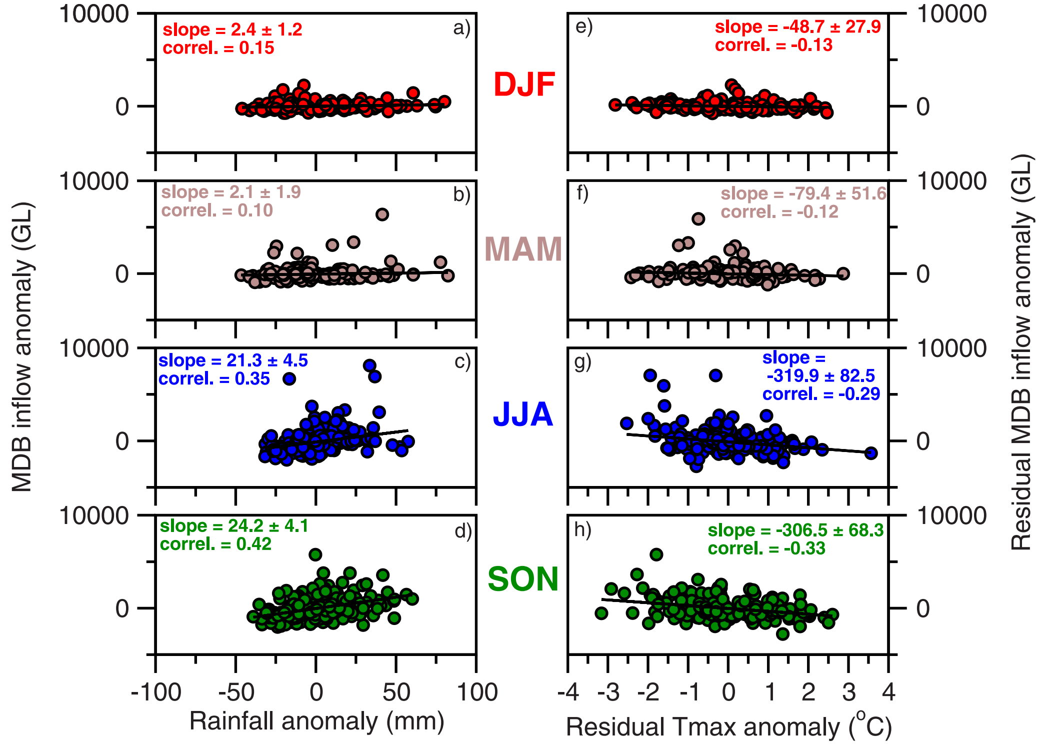

Figure 4. Scatter diagram of (a–d) monthly mean MDB rainfall anomalies versus monthly-total inflow anomalies to the Murray Darling River System for DJF, MAM, JJA, and SON, respectively, and (e–h) monthly-mean residual Tmax anomalies versus monthly-total residual inflow (see section 2), for DJF, MAM, JJA, and SON, respectively. All data are linearly detrended. The correlation in (c), (d), (g), and (h) is greater than 0.27, significant at the 95% confidence level.

reduction trend, and that there is a contribution from rising temperatures. Our results indicate that a rise of 1°C in temperature leads to a 15% reduction in the annual inflow, even if rainfall does not change. The negative impact of rising temperature is unlikely to be offset by an increase in rainfall, as most climate models are projecting a rainfall reduction. Therefore we can expect more occurrences of low MDB inflow, as observed in more recent years. We stress that a comprehensive assessment must be carried out through detailed hydrological modelling. However, our results do highlight a potentially significant impact from rising temperatures.

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