18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

# Are declining river inflows linked to rising temperatures? A perspective from the Murray-Darling Basin.

**Cowan, T. D.** [1] **and W. Cai** [1]

[1] *CSIRO Marine and Atmospheric Research*
*Email: tim.cowan@csiro.au*

**Abstract:**

In recent years, rainfall across the Murray-Darling Basin (MDB) was well below the long-term average, but not unprecedented. In contrast, streamflows to Australia's longest river system, the Murray-Darling, reached a historical low. Here we examine the possible causes for this disparity. Although annual total inflow is more sensitive to rainfall fluctuations over south eastern Australia, where rainfall over recent years has been the lowest over the entire record, this alone is unable to explain the observed decreasing trend in inflow. A relationship exists between inflow variations and fluctuations of temperature not associated with rainfall in austral winter and spring: a rise of 1°C leads to an approximate 15% reduction in the climatological annual MDB inflow. Our results provide a strong link between rising temperatures, due to the enhanced greenhouse effect, and the impact this has on Australia's water resources, in addition to any reduction in rainfall. Future conditions of MDB inflows will be discussed with reference to climate-model projections.

***Keywords:*** *Rising temperature, inflow reduction, climate change.*

## 1. INTRODUCTION

The possibility that rising temperatures have exacerbated the impact of recent Australian droughts has been a topic of public and scientific interest (Nicholls, 2004; Karoly et al. 2003). Australia is one of the driest inhabited continents, with high natural variability of rainfall due in part to the El Niño-Southern Oscillation. Rainfall leads to cooling due to increased cloud cover and enhanced evaporation (Nicholls et al. 1996; Jones and Trewin, 2000). Rising temperature is expected to increase the evaporative loss and water demand from plants, contributing to a reduction in soil moisture, however, historical soil moisture data are inadequate to provide such evidence. Long-term inflows to major rivers are a useful surrogate, as they are generated when soil moisture is high.

In the past decade, rainfall over the catchments of Australia's longest river system, known as the Murray Darling Basin (MDB), was well below the long-term average, but not unprecedented. By contrast, inflows to this river system, located in south-eastern Australia (see Figure 1a), reached a historical low. During the drought at the turn of the 19th century (1895-1902) the average inflow was 5400 GL $yr^{-1}$ (1 GL = $10^9$ L), compared to the long-term average of 11, 200 GL $yr^{-1}$ (Figure 1a). A previous 12-month minimum was recorded during 1914–1915 at 1920 GL $yr^{-1}$. During the 2000-2007 drought, the average inflow was 4150 GL $yr^{-1}$. 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 $yr^{-1}$ (Figure 1b). Does this constitute evidence of an impact from rising temperature? We examine the relationship of inflow with temperature and rainfall over the MDB in the late 20$^{th}$ century.

## 2. DATA AND METHOD

The time series of monthly total inflow to the Murray-Darling river system is provided by the MDB Authority, an Australian government management agency. The gauged inflows include those from the Murrumbidgee, Goulburn, Campaspe, Loddon and Darling Rivers, 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.

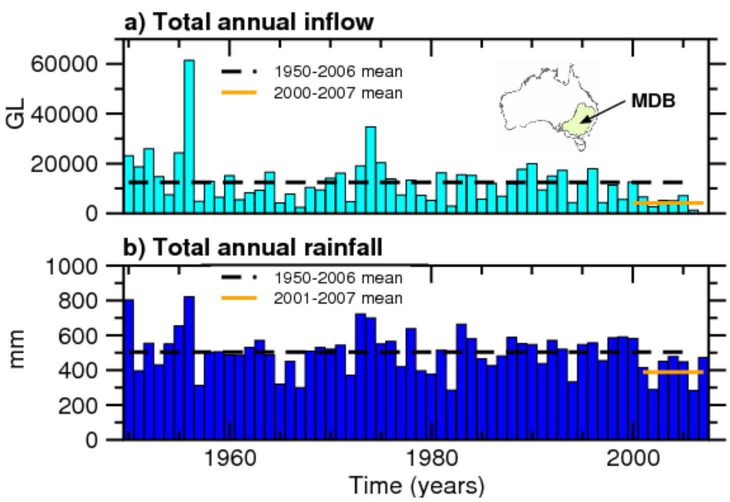


**Figure 1.** (a) Time series of annual-total inflow to the MDB, with an insert showing the region of interest (light green area) and (b) annual-total rainfall averaged over the MDB.

Monthly rainfall averaged over the MDB, along with gridded monthly rainfall and maximum temperature (Tmax), subjected to extensive quality control (Torok, 1996), are provided by the Australian Bureau of Meteorology (BoM). The monthly average of daily Tmax BoM data sets start from 1950. Raw data and anomalies are referenced to the 1950-2006 climatology, which shows that most of the inflow is generated in the region's wet season (June to November), when the southern MDB rainfall is strong, and evaporation is low. Exceptions occur when there is heavy summer rain in the northern sub-catchments due to tropical lows (including tropical cyclones), troughs and depressions.

As alluded to previously, fluctuations of rainfall and temperature are not independent, as rainfall events lower daily Tmax and hence the daily average temperature due both to increased cloud cover (reduced daytime radiative warming) and increased evaporative cooling. We aim to establish a relationship between inflow and the component of Tmax that is unrelated to rainfall variations, hereafter referred to as the residual Tmax. We regress Tmax onto raw rainfall time series for each individual month and on each grid point. This gives us the Tmax variability that is related to rainfall, which is then subtracted from the raw Tmax. Residual monthly-mean Tmax and residual season-total inflow (i.e. inflow unrelated to rainfall anomalies) are then constructed. Thereafter, the data are linearly detrended to remove any long-term coherence. Figure 2 shows that the removal of rainfall influence on Tmax is complete. This method of residual analysis follows on from the partial regression/correlation approach of Nicholls (2004), who showed that when "rainfall associated" variability is removed from mean maximum temperatures over the MDB an increasing residual temperature trend still exists. This makes the approach of linear regression analysis appropriate for this study as we are looking at inflows and temperatures over a large spatial region.

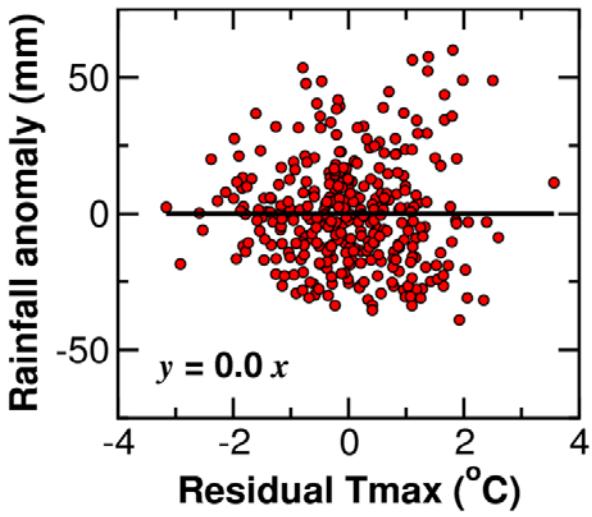


**Figure 2**. Scatter diagram of residual Tmax (°C) versus rainfall (mm) over Australia's MDB. Shown are anomalous monthly-mean residual Tmax and anomalous monthly-total area averaged rainfall (mm) for the wet season (June to November). The residual Tmax is obtained by removing the influence of rainfall from raw data. Linear line of best fit is indicated (thick black line) which shows that there is no relationship, e.g. the slope and correlation are zero (sample size = 6×57 months).

## 3. THE RELATIONSHIP BETWEEN MDB INFLOW AND CLIMATE VARIABLES

The relationship between anomalies of annual-total inflow and rainfall averaged over the MDB is strong with a correlation of 0.71 (Figure 3a). 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 (June-August; or JJA) and spring (September-November; or SON) seasons. Although the conversion rate in austral autumn (March-May; or MAM) *per se* is low, rainfall in this season is important for annual-total inflow (Figure 3b), with conversion rate to annual inflow of 55 GL $mm^{-1}$. This means that autumn rainfall across the basin is important for the annual-inflow total. By contrast, the autumn conversion rate to autumn inflow is low (6 GL $mm^{-1}$) indicating a soil ''wetting mechanism'' by autumn rain with delayed impacts on the proceeding seasons. MDB rainfall experiences a greatest reduction in autumn, as with much of southeast Australia. However, as will be shown, this seasonality of rainfall reduction is just one component for the unprecedented inflow decline; the other it is a case of higher temperatures (e.g. Tmax).

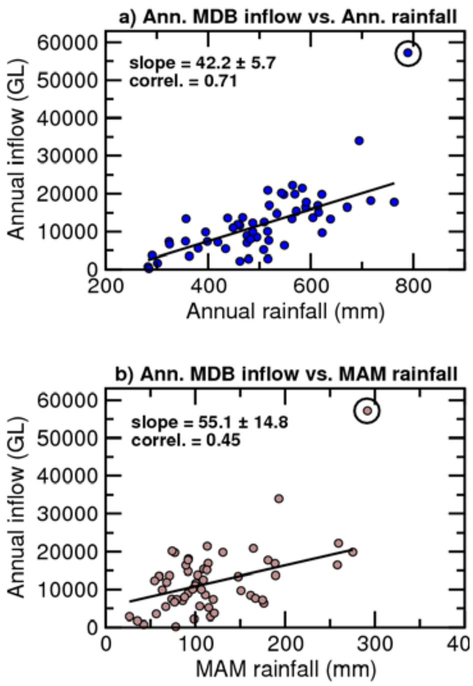


**Figure 3**. (a) Scatter diagram of annual-total MDB rainfall versus annual-total inflow to the Murray Darling River System. (b) Scatter diagram of MAM MDB rainfall versus annual-total inflow to the Murray Darling River System. All data are linearly detrended, and the analysis is carried out without 1956 data (circled). A correlation greater than 0.27 is significant at the 95% confidence level.

In JJA and SON, the correlation between residual seasonal-total inflow and residual seasonal-mean Tmax (Figures 4a and 4b) 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 correlations in December-February (or DJF) and MAM are weak, and less spatially uniform over the MDB. The relationship between residual seasonal total inflow and residual minimum temperature (Tmin) is generally weaker than that with residual Tmax, particularly in JJA and SON, when the impacts of rising temperature are apparent. 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.

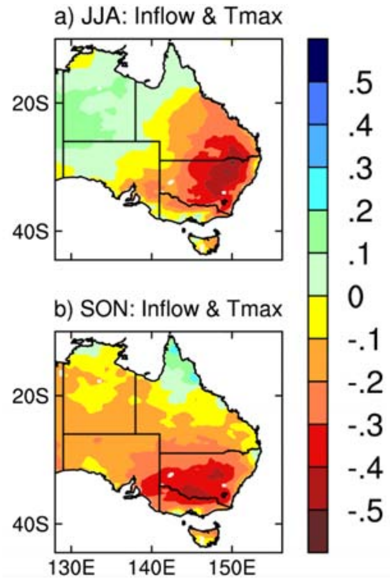


**Figure 4**. Maps of correlations between MDB residual total inflow and residual mean maximum temperature for (a) winter (June, July, August, or JJA) and (b) spring (September, October, November, or SON). All data are linearly detrended, and the analysis is carried out without 1956 data.

## 4. OBSERVED MDB INFLOW FLUCTUATIONS SINCE 1950

The sensitivity of residual inflow to residual Tmax (Figures 5) in JJA and SON is statistically significant, at 312 GL °C$^{-1}$ per month, 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.

### 3.1 Contribution from the Rainfall Reduction and Temperature Increase

Since 1950, the annual-total rainfall over the MDB (Figure 1b) has decreased by about 56 mm based on a linear regression. Using this value and the relationship in Figure 3a, the rainfall decline contributes to about 33% of the observed inflow reduction (since 1950). 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., the state of Victoria) is greater than that over the MDB as a whole in MAM, JJA, and SON, particularly in MAM. Inflow is sensitive to southern MDB rainfall (figure not shown), with MAM rainfall particularly important (Figure 3b). Will these non-uniform features lead to a larger contribution from rainfall? To address this issue, we calculate the Victoria rainfall

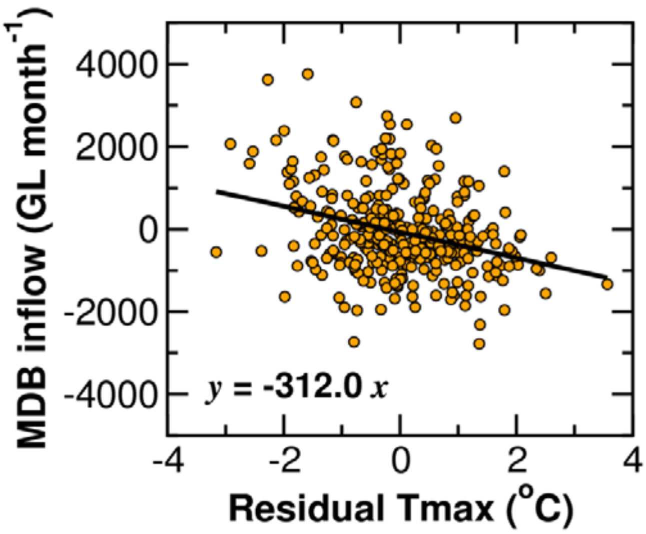


**Figure 5**. Scatter diagram of residual Tmax (°C) versus inflow (GL) to the MDB. Shown are anomalous monthly-mean residual Tmax and anomalous monthly-total inflow for the wet season (June to November). The residual Tmax is obtained by removing the influence of rainfall from raw Tmax (Nicholls, 2004). Linear line of best fit (thick black line) is indicated with a correlation of -0.31, statistically significant at a 99% confidence level. The standard error is 52.3 GL °C$^{-1}$ month$^{-1}$, or 17% of the slope, which is 312 GL °C$^{-1}$ month$^{-1}$.

reduction since 1950 for each season, and assume that the Victoria rainfall reduction is experienced throughout the entire MDB. Using rainfall-inflow conversion rates for each season, 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.

Since 1950, residual Tmax has increased by 0.94°C in JJA and 1.02°C in SON, which in some part is due to greenhouse warming (Nicholls et al., 1996; Nicholls, 2003). Following the inflow-Tmax relationship (Figure 5), this would contribute to 1929 GL, which accounts for about 27% of the total inflow reduction, comparable to the rainfall component.

How do these results compare with other approaches to the inflow – temperature problem? One such study (Fu, 2009), using a streamflow-precipitation-temperature relationship and two-parameter climate elasticity of streamflow (Fu et al., 2007a, b), showed that a rainfall reduction alone across the MDB is unable to account for the observed inflow reduction. However, the study also showed the non-linear dependence of streamflow on temperature. The study pointed to a 35% decrease in streamflow with a 20% precipitation decrease when the mean MDB temperatures. If temperatures were to rise 0.4°C this would lead to a 45% decrease in streamflows. The author is quick to point out that many uncertainties still remain including data quality, the independence of land surface changes with temperature, and the lack of temporal resolution in their model.

## 5. WHAT DOES THE FUTURE HOLD FOR INFLOWS TO THE MDB?

The future of inflow throughout the MDB depends upon the future rainfall and temperature changes. 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. 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 occurs 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). If we assume that the relationship shown in Figure 3a 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. If the relationship between Tmax and inflow in JJA and SON (Figure 5) persists into a future climate, a 2°C increase by 2060 (the mid-range A1B scenario) will reduce the inflow by about 3750 GL (total for JJA and SON), or about 30% of the present-day mean inflow, comparable to that due to a rainfall reduction.

This analysis is consistent with previous studies that suggest rising temperatures are exacerbating the impact of the present dry period. The economic impacts of these declines in inflows also need to be considered. For example, with water at a price of 50¢ per 1000 litres, the direct economic loss is about $900M, however this does not include flow-on impacts.

## 6. CONCLUSIONS

Our analysis reinforces the notion that a rainfall reduction alone is unable to explain the observed inflow reduction trend across the MDB, and that there is a contribution from rising temperatures. Our results indicate that a reduction of 312 GL month$^{-1}$ is associated with a rise of 1°C (Figure 5). This amounts to a total reduction of over 1800 GL °C$^{-1}$ in the wet season (JJA and SON) alone, equivalent to an approximate 15% reduction of the climatological inflow for a 1°C temperature rise. The relationship explains why, during the present drought, inflow to the MDB has reached the lowest level on record, and implies that the recent warming is partially responsible for the decline. The Intergovernmental Panel on Climate Change Fourth Assessment Report projects a range of temperature rise of 1°C - 3°C by 2050 (Christensen et al. 2007). If this linear relationship persists, it would lead to a 15% - 45% reduction of inflow to the MDB. This would greatly exacerbate the impact of a projected 10-15% rainfall reduction.

**ACKNOWLEDGMENTS**

We thank the MDB Commission for providing the inflow data, the BOM for providing monthly gridded climate data, and our many colleagues for stimulating discussion on the related research. This research was supported by the Department of Climate Change.

**REFERENCES**

Ashrit, R. G., K. R. Kumar, and K. K. Kumar (2001), ENSO-monsoon relationships in a greenhouse warming scenario, Geophys. Res. Lett., 28, 1727–1730.

Christensen, J. H., et al. (2007), Regional climate projections, in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon et al., pp. 847–940, Cambridge Univ. Press, New York.

Cai, W. J., H. H. Hendon, and G. Meyers (2005), An Indian Ocean dipole in the CSIRO coupled climate model, J. Clim., 18, 1449–1468.

Fu, G.B (2009), Impacts of precipitation and temperature changes on annual streamflow in the Murray-Darling Basin. (in preparation).

Fu, G.B., M. E. Barber, and S.L. Chen (2007a), The impacts of climate change on regional hydrological regimes in the Spokane River watershed, J. Hydrol. Eng., 12, 452–461.

Fu, G.B., S. P. Charles, and F. H. S. Chiew (2007b), A two-parameter climate elasticity of streamflow index to assess climate change effects on annual streamflow, Water Resour. Res., 43, W11419, doi:10.1029/2007WR005890.

Hu, Z.-Z., M. Latif, E. Roeckner, and L. Bengtsson (2000), Intensified Asian summer monsoon and its variability in a coupled model forced by increasing greenhouse gas concentrations, Geophys. Res. Lett., 27, 2681–2684.

Jones, D. A., and B. C. Trewin (2000), On the relationships between the El Niño –Southern Oscillation and Australian land surface temperature, Int. J. Climatol., 20, 697–719.

Karoly, D. J., J. Risbey, A. Reynolds, and K. Braganza (2003), Global warming contributes to Australia's worst drought, Australasian Science, April 2003 issue, 14–17.

Lavery, B., G. Joung, and N. Nicholls (1997), An extended high quality historical rainfall data set for Australia, Aust. Met. Mag. 46, 27–38.

Nicholls, N. (2003), Continued anomalous warming in Australia, Geophys. Res. Lett., 30(7), 1370, doi:10.1029/2003GL017037.

Nicholls, N. (2004), The changing nature of Australian droughts, Clim. Change, 63, 323–336.

Nicholls, N., B. Lavery, C. Frederiksen, W. Drosdowsky, and S. Torok (1996), Recent apparent changes in relationships between the El Niño–Southern Oscillation and Australian rainfall and temperature, Geophys. Res. Lett., 23, 3357–3360.

Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata (1999), A dipole mode in the tropical Indian Ocean, Nature, 401, 360–363.

Torok, S. J. (1996), thesis, University of Melbourne, Melbourne, Australia.