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The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society

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[1] The "Millennium Drought" (2001–2009) can be described as the worst drought on record for southeast Australia. Adaptation to future severe droughts requires insight into the drivers of the drought and its impacts. These were analyzed using climate, water, economic, and remote sensing data combined with biophysical modeling. Prevailing El Niño conditions explained about two thirds of rainfall deficit in east Australia. Results for south Australia were inconclusive; a contribution from global climate change remains plausible but unproven. Natural processes changed the timing and magnitude of soil moisture, streamflow, and groundwater deficits by up to several years, and caused the amplification of rainfall declines in streamflow to be greater than in normal dry years. By design, river management avoided impacts on some categories of water users, but did so by exacerbating the impacts on annual irrigation agriculture and, in particular, river ecosystems. Relative rainfall reductions were amplified 1.5–1.7 times in dryland wheat yields, but the impact was offset by steady increases in cropping area and crop water use efficiency (perhaps partly due to CO_2 fertilization). Impacts beyond the agricultural sector occurred (e.g., forestry, tourism, utilities) but were often diffuse and not well quantified. Key causative pathways from physical drought to the degradation of ecological, economic, and social health remain poorly understood and quantified. Combined with the multiple dimensions of multiyear droughts and the specter of climate change, this means future droughts may well break records in ever new ways and not necessarily be managed better than past ones.

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1. Introduction

1.1. Millennium Drought

[2] In the years before 2010, southeast Australia suffered the driest period since 1900 by several measures, with consequences for ecosystems, economy, and society. Published drought assessments used different criteria to determine the start and end of the drought and accordingly found different periods: the *Commonwealth Scientific and Industrial Research Organisation (CSIRO)* [2010] found that the period 1997–2009 had the lowest average rainfall since 1900 (but with some above-average precipitation years), whereas *Van Dijk and Renzullo* [2009] found that surface water resources scarcity already started to develop around 1994. Here, we define the Millennium Drought as the period 2001–2009: the longest uninterrupted series of years with below median rainfall in southeast Australia since at least 1900 (Bureau of Meteorology data; http://www.bom.gov.au/cgi-bin/climate/change/timeseries.cgi). The end of the drought is less ambiguous: a strong La Niña event in early 2010 brought very high precipitation and large-scale flooding to many parts of southeast and east Australia [*Beard et al.*, 2011]. (However, 2010 was also the driest year on record in southwest Australia, which is little affected by El Niño Southern Oscillation (ENSO); continuing more than three decades of strong rainfall decreases in its coastal regions [*Ryan and Hope*, 2006]).

[3] Australia's instrumental record is sparse before 1940 and few locations have continuous rainfall measurement

All Supporting Information may be found in the online version of this article.

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before 1900. Combined with rainfall that is highly variable at seasonal, annual, and decadal time scales [e.g., *Kiem and Franks*, 2004; *Verdon-Kidd and Kiem*, 2010], this makes it difficult to determine how unusual the Millennium Drought was in a long-term context. Palaeoclimate records show that long dry periods have occurred in the past [*Verdon-Kidd and Kiem*, 2010; *Verdon and Franks*, 2006], although recent analyses calculated a 97%–98% probability that the recent drought was the most severe since 1783 (i.e., around European settlement) and could have a return period of as much as 1500 years—at least if climate can be assumed stationary over this time scale [*Gallant and Gergis*, 2011; *Gergis et al.*, 2012].

1.2. Drought Impacts

[4] Particularly severely hit by the Millennium Drought were river ecosystems and irrigated and dryland agriculture in Victoria and the Murray-Darling Basin (MDB), Australia's largest river system [*Leblanc et al.*, 2012]. Drought also contributed to the enforcement of water restrictions in most major cities, to increased electricity prices, and to major bushfire events in 2003 and 2009. At a global scale, Australia's drought was the main cause of an apparent reversal in water cycle intensification [*Huntington*, 2006] observed in previous years, raising questions about the likelihood of further intensification in future [*Jung et al.*, 2010].

[5] Droughts and their impacts can be categorized as meteorological, hydrological, agricultural, and socioeconomic [*Mishra and Singh*, 2010; *Thomas*, 1965]. The contributions of climate change, water management, and other natural or human factors to these impacts need to be understood to guide our expectations about, and response to, future droughts. For example, if some part of drought impacts can be attributed to global warming, more frequent and more severe events may be expected in future [*Milly et al.*, 2008]. Where human actions have contributed to drought impacts, this suggests opportunities to adapt and prepare for future events [*Vörösmarty et al.*, 2000].

[6] Unambiguous isolation of the factors contributing to drought and its impacts is difficult. The short record and variable climate was already mentioned. In addition, hydrological processes can respond in a highly nonlinear and delayed way to meteorological conditions due to storage effects and losses that accumulate along water transport and distribution networks. Finally, natural climate, water cycle, and vegetation processes interact with water resources management, agriculture, economy, and society in a myriad of ways.

1.3. Objective

[7] Our main objective was to isolate and quantify anthropogenic and natural contributions to the Millennium Drought and its impacts. Because of the complexity of the causes of the meteorological drought, its propagation through the water cycle and its impacts on ecosystems, agriculture, economy, and society, we explored multiple lines of observational evidence, connecting drought impacts to their causes and amplifying factors where possible. We compared the observations with expectations based on hydrological process models and simple statistical models and discussed our findings in the context of previously published analyses. We focused on three questions:

[8] (1) What were the main climatological causes of the meteorological drought and can a human influence be detected, or be expected in future droughts?

[9] (2) How did the meteorological drought propagate through the water cycle and impact on ecosystems, agriculture, economy, and society?

[10] (3) What are the implications for adaptation to mitigate the impact of future droughts?

[11] Data analyses were performed to address questions (1) and (2) and these are the focus of sections 2 and 3. For readability, some of the details are provided in the supporting information. In section 4, the results of the analysis are discussed in the context of published studies. Finally, in section 5 a synthesis is provided, in which the range of observed impacts and processes is put within a conceptual framework, and the implications of our results for managing and mitigating future droughts are discussed.

2. Materials and Methods

2.1. Causes of the Meteorological Drought

[12] It is common practice to evaluate plausible linkages between observed regional rainfall anomalies and any skewness or changes in large-scale modes of variability previously identified to influence interannual rainfall patterns [*Nicholls*, 2006]. While such analyses are not attribution studies in any strict sense, they can help to interpret observed rainfall anomalies. Following this approach, the anomalously low rainfall conditions in southeastern Australia during the Millennium Drought have been linked to a combination of intensification of the mean sea level pressure across southern Australia [*Hope et al.*, 2010] and particularly the subtropical ridge, a belt of high-pressure systems that expresses the descending branch of the Hadley cell [*Timbal et al.*, 2010], as well as to ENSO [e.g., *Verdon-Kidd and Kiem*, 2009b]. An influence of the Indian Ocean Dipole (IOD) has been proposed [*Cai et al.*, 2009; *Ummenhofer et al.*, 2009] but also questioned [*Smith and Timbal*, 2012; *Timbal and Hendon*, 2011]; the same is true for the Southern Annular Mode (SAM) [*Hendon et al.*, 2007; *Meneghini et al.*, 2007; *Nicholls*, 2010; *Verdon-Kidd and Kiem*, 2009a]. To a considerable extent, different conclusions about the relative importance of different drivers appear to be a result of methodological differences: in the analysis method; in the metrics (indices) used to describe each phenomenon; in the region, time period, and time scale of variability considered; and other, more subtle choices made in the analysis.

[13] We examined if stronger inferences could be made if both predictand and predictors were averaged over larger areas and periods. This should reduce random components and noise in the data and allow for lagged correlations due to landscape hydrometeorological memory and any delayed atmospheric response to ocean circulation indices [*Koster et al.*, 2004; *Timbal et al.*, 2002]. We compared our statistical results based on indices with published research on the drivers of Australian rainfall in general, and during the drought in particular.

[14] Daily rainfall estimates for the Australian continent were derived by interpolation of daily rainfall gauge readings to a 0.05° grid [*Jeffrey et al.*, 2001]. The gridded data were combined with a vector map showing 245 river basins

identified by the Australian Water Resources Council (Map 5) [*AWRC*, 1975]. For each AWRC basin, a time series of basin-average annual rainfall was calculated for 1900–2009. A matrix of fraction covariance (squared correlation coefficient, R^2) between each time series pair was calculated. The software package *MultiDendrograms 2.1* [*Fernández and Gómez*, 2008] was used to cluster basins by interannual rainfall patterns. As a distance measure, the fraction of uncorrelated variance ($1 - R^2$) was used. Seven metaclusters were derived from the cluster dendrogram, and these were merged into six large, contiguous regions through minor editing (see supporting information).

[15] For each of the six regions a time series of annual average rainfall was calculated. These time series were compared to time series of nine predictor indices describing six candidate phenomena: the ENSO (Nino3.4 [*Kaplan et al.*, 1998] and Southern Oscillation Index (SOI)); IOD mode index and the classification of *Ummenhofer et al.* [2009]; Pacific decadal Oscillation (PDO) [*Zhang et al.*, 1997]; SAM [*Marshall*, 2003; *Visbeck*, 2009]; global mean temperature (GMT); Hansen index); and the intensity and location of the Southern Hemisphere Subtropical Ridge (STRI and STRL) [*Drosdowsky*, 2005]. Full details and data sources are listed in the supporting information. Where monthly or seasonal predictor data were available, these were used to first calculate mean seasonal values (December-February and so on) as well as annual average values, producing five candidate predictor variables. All resulting climate predictor time series were normalized by their mean and standard deviation and any missing values replaced by the mean (i.e. zero, after normalizing).

[16] Five-year rolling averages were calculated for the predictors ($x_{1..n}$) as well as the regional rainfall averages ($y_{1..6}$) for the period 1900–2009 (shorter and longer integration periods were also tested, with very similar results). For each region, a multivariate model was fitted by regression against residuals in four steps:

$$P_{\mathrm{est}} = c_0 + c_1x_1 + c_2x_2 + c_3x_3 + c_4x_4, \tag{1}$$

where indices $x_{1..4}$ were selected at each respective step as those having the greatest correlation with the residual unexplained variance (i.e., the highest partial correlation). The coefficients $c_{0..4}$ were found through linear regression. From the associated fraction of variance explained (R^2), we calculated Akaike's information criterion (AIC) [*Akaike*, 1974] to decide whether to accept the four-variable model or whether to select one with fewer predictors:

$$\mathrm{AIC} = n\ln\frac{1-R^2}{\mathrm{n}} + 2k, \tag{2}$$

where k is the number of free parameters ($c_0..c_i$; 2 to 5) and n the number of independent observations. Although the total number of years was 110, the 5 year averaging would have introduced autocorrelation; therefore, we conservatively estimated n as 22 (110 years divided by 5). It is noted that the assumption of $n = 110$ for the original time series should be considered a rough estimate only: effective sample size could potentially be further reduced by serial correlation in the original time series [*Yue and Wang*, 2004], and calculating the 5 year rolling averages may not have removed all of that serial correlation.

[17] The contribution of each of the climate phenomena to the meteorological drought was estimated by multiplying the observed 2001–2009 anomaly in $x_{1..4}$ by the sensitivity of rainfall to $x_{1..4}$, defined by the slope $c_{1..4}$ of the regression model (equation (1)).

[18] To assess whether the drought reflected a gradual change, linear trends and associated significance were calculated for each region using annual rainfall data for 1950–2009. The contribution to each identified driver to rainfall trends was estimated as

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \frac{\mathrm{d}P}{\mathrm{d}x_i}\frac{\mathrm{d}x_i}{\mathrm{d}t} = c_i\frac{\mathrm{d}x_i}{\mathrm{d}t}. \tag{3}$$

[19] That is, the contribution of each phenomenon to observed rainfall trends ($\mathrm{d}P/\mathrm{d}t$) was estimated as the product of the trend in the index ($\mathrm{d}x_i/\mathrm{d}t$) and the sensitivity c_i. It should be emphasized that the calculation of linear trends is inevitably contingent on the period chosen, regardless of statistical significance. For example, in southeast Australia 1950 marks the start of a comparatively wet period (see section 3); therefore, choosing an earlier or later start date would likely have led to a diminished and enhanced trend, respectively.

2.2. Hydrological Drought Impacts

[20] Due to nonlinearity in catchment hydrological functioning, relative changes in annual rainfall are typically amplified a few times in streamflow generation during non-drought years [*Budyko*, 1974; *Chiew*, 2006]. To determine the amplification of rainfall deficits in streamflow during the drought, we used observed catchment streamflow data as well as two alternative modeling approaches.

[21] Daily streamflow data was obtained from government agencies in New South Wales, Queensland, Victoria, Tasmania, and West Australia. Out of the available streamflow data, initially data was selected for 466 gauged catchments in the five drainage divisions most affected by the drought: Southeast Coast, Tasmania, MDB, South Australian Gulf, and Southwest Coast. All data were quality controlled and any interpolated data were removed. Terrain analysis was carried out using a digital elevation model to determine the catchment area of each of the catchments. Each individual catchment was visually assessed against topographic maps and satellite photography to ensure it was not affected by significant irrigation, impoundments, or other forms of regulation. For each catchment, streamflow (Q in mm) was aggregated from daily to monthly totals (by multiplying mean daily Q by the number of days in the month, provided more than 70% of days had data) and subsequently to annual totals. Missing months were gap-filled by considering the runoff coefficient (r_c, that is, the ratio of total streamflow Q over total rainfall, P, for the year) and subsequently multiplying r_c with P for the missing months. Gaps were filled only if less than 4 months were missing for a given year. Out of the 466 gauged catchments, 126 catchments were selected that had 30 or more years of observations before the drought and at least three years during the drought (2001–2009). Annual rainfall for the same catchments and years was derived by overlaying the catchment map with the rainfall grids.

[22] To determine to what extent streamflow reductions during the drought were different from those that could be expected in normal dry years, the observed relative streamflow declines were compared to predictions by two alternative modeling methods: a simple conceptual/statistical model that ignores temporal correlation or subannual rainfall patterns, and a daily time step process model.

[23] The simple model was a two-parameter rational function fitted to predrought annual rainfall and streamflow data. The nonlinearity between rainfall and streamflow expected under stationary conditions was estimated by fitting the model:

$$Q_e = \frac{P}{1 + \frac{P}{a} + b\left(\frac{a}{P}\right)^2}. \quad (4)$$

[24] This model is mathematically near identical to the model proposed by *Zhang et al*. [2001] based on *Budyko* [1974] theory, where a would represent potential evapotranspiration (PET) and b a fitting parameter. For each catchment, we fitted values for both a and b rather than prescribing a value. Hence, the resulting estimate represents the influence of rainfall changes, but potentially including any covariance between P and PET. The model was fitted to the rainfall and observed streamflow data before 2001. Subsequently, the fitted model was used to predict streamflow for the drought years. For most catchments, records before 2001 did not include a drought as severe as the Millennium Drought and this could influence the fitted model. This was indeed the intention: comparing observed and model-predicted impacts should indicate to what extent catchment behavior during the drought was different from normal dry years.

[25] The process model used is the landscape hydrological model of the Australian Water Resources Assessment (AWRA) system [AWRA-L version 0.5; *Van Dijk*, 2010; *Van Dijk and Warren*, 2010; *Van Dijk and Renzullo*, 2011]. It considers catchment storage dynamics and observed weather patterns, including the potential role of increased radiation or temperature [e.g., *Cai and Cowan*, 2008; *Potter and Chiew*, 2011]. AWRA-L may be described as a hybrid between a simplified land surface model and a lumped catchment model. Grid resolution, domain, and the number of subgrid land cover classes are not prescribed but defined by the model inputs. The model evolves on a daily time step, and for each cover class simulates the water balance of a top soil, shallow soil, and deep soil compartment as well as vegetation phenology in response to water availability; whereas groundwater and surface water dynamics are estimated at grid resolution. It considers two land cover classes (deep- and shallow-rooted vegetation). Forcing was from the daily rainfall grids (section 2.1) and similarly interpolated grids of shortwave radiation and minimum and maximum temperature [*Jeffrey et al*., 2001]. The model was run for the period 1895–2010 with default parameterization [*Van Dijk*, 2010], that is, the model was not optimized to reproduce the streamflow observations used in the analysis. The daily streamflow grids were combined with the catchment map and time series of catchment average streamflow (in millimeters per day) were calculated for each catchment.

[26] For each catchment, the observed and predicted reductions were estimated as the relative difference between the streamflow observed or predicted for the drought years (2001–2009) and the predrought years. In each case, only those years for which observations were available were selected. A test was done to assess the differences in model-estimated and observed runoff declines against those predicted for normal dry years: for each catchment the pre-2001 years with rainfall in the lowest quintile were selected, and the relative reductions in rainfall, model-estimated streamflow, and observed streamflow were compared.

[27] To help interpret the AWRA streamflow estimates, we compared model estimated total water storage with satellite observations. Satellite terrestrial water storage (TWS) data were available from the Gravity Recovery and Climate Experiment satellite mission (GRACE) [*Tapley et al*., 2004]. GRACE provides integrated estimates of variations in total TWS based on precise observations of Earth's time variable gravity field. We used the 1° resolution gridded estimates provided by the GRACE Tellus website and produced by the University of Texas Centre for Space Research (CSR). The data preprocessing and analysis was described in *Van Dijk et al*. [2011].

2.3. Ecological Drought Impacts

[28] We considered impacts on dryland and riverine ecosystems separately. Apart from the impacts of the drought on dryland agriculture (section 2.4), we did not attempt to quantify impacts on dryland ecology. Judging by the impact on living biomass, they are likely to have been widespread, however (Figure 1a; see section 4).

[29] The impacts of drought on ecosystems are diverse [*Bond et al*., 2008] and an integrated measure of drought impacts on riverine ecosystems is therefore hard to define [*Vörösmarty et al*., 2010]. In the MDB, the impacts that attracted most media attention included toxicity in the lakes at the end of Murray River due to low river inflows and large scale floodplain forest mortality throughout the basin due to lacking flood events [*Leblanc et al*., 2012]. In this study, we used total flows and the occurrence and level of flooding in the Lower Murray River as indicators of those respective drought impacts.

[30] Measured river flow in the Lower Murray River was compared with estimates from a digital model of the MDB river system (explained below) from which all regulation infrastructure and extractions were removed. Daily streamflow data for the Lower Murray at a location for which streamflow was simulated by the river model (gauge 425010 at Wentworth, near the confluence with the Darling River, Figure 1b) were available from 1968 onward from New South Wales Department of Natural Resources.

[31] The river model was developed as part of a large project commissioned by the Australian Governments [*CSIRO*, 2008a]. Daily time series of flows in the absence of regulation were reconstructed for the period 1895–2006 using a comprehensive set of models simulating flows, losses, and diversions in the various individual rivers contributing to the MDB, as a function of tributary inflows and operation of the storages and infrastructure in the river system. Tributary inflows were observed streamflow records wherever available, missing data were interpolated using rainfall-runoff models or regression models based on observed data. It is noted that the unimpeded scenario is

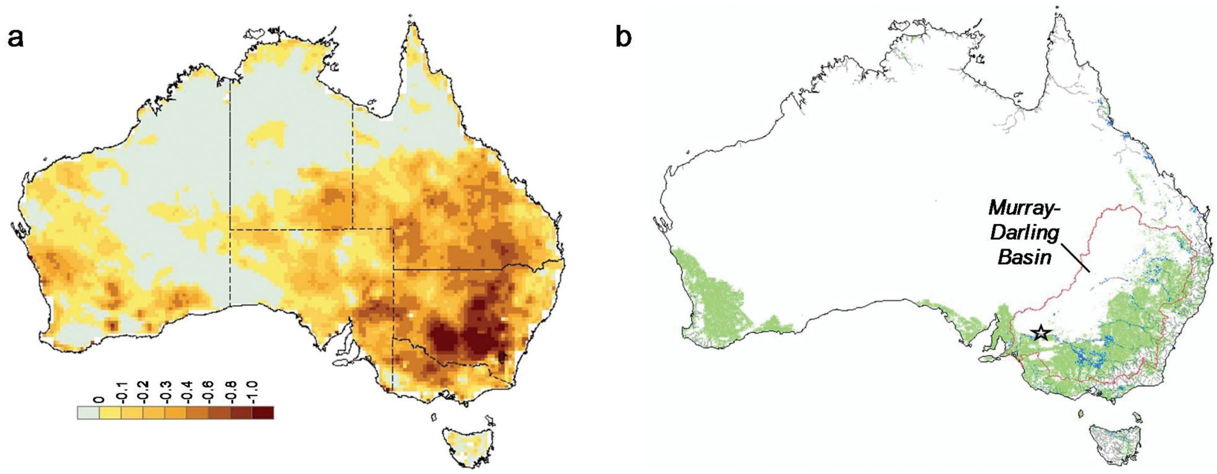

Figure 1. (a) Map of the difference between mean remotely sensed vegetation water content (VOD, in dimensionless units) for 2001–2009 and 1978–2000. (b) Location of the intensive cropping (green) and irrigated agriculture (blue) zones, the MDB (red) and the Murray River at Wentworth (star symbol).

not equal to a scenario without any development; the tributary inflows are the same in both scenarios and reflect historic land use changes and smaller structures such as private farm dams [*CSIRO*, 2008a]. From the observed and modeled data, the average observed and reconstructed unimpeded flows for the available drought years were calculated. The observed and modeled time series of annual flow volumes and annual maximum flood were compared.

2.4. Agricultural Drought Impacts

[32] In economic terms, half of Australia's agricultural production is from irrigated agriculture (28%) and grain cropping (22%) [*Australian Bureau of Statistics (ABS)*, 2011], and therefore, data for these crops were analyzed in more detail. The impact of water resources availability on irrigated agriculture was comparatively straightforward to determine using ABS data on crop production. The impact on dryland grain production is more difficult to estimate and attribute for several reasons, including the ongoing improvement in crop water use efficiency (WUE) due to agricultural innovation (e.g., see *Nicholls* [1997] and published comments). Details follow below, but in brief, we compared 33 year time series of wheat production, crop area and yield [*ABS*, 2011] with three crop growth indicators: (1) vegetation water content derived from passive microwave remote sensing (vegetation optical depth, VOD, an indicator of living biomass) (Figure 1a), (2) crop greenness (normalized difference vegetation index, NDVI, responding to canopy cover and leaf chlorophyll content); and (3) crop water use (transpiration) estimated by the AWRA model. A map of intensive cropping areas [*National Committee for Land Use and Management Information (NCLUMI)*, 2009] (Figure 1b) was used to calculate annual mean NDVI, VOD, and crop water use over the wheat cropping areas. For each of these growth indicators, a model was constructed that predicted wheat yield by multiplying a linear response to the indicator by an annually increasing conversion efficiency. Drought impact was estimated by comparing actual wheat yields to potential yield estimated from average predrought indicator values.

[33] We used the VOD product of *Liu et al*. [2007, 2009, 2011], developed by blending VOD retrievals from a series of passive microwave satellites (SSM/I, SMMR, TRMM, and AMSR-E). NDVI data were available from five partly overlapping time series: one derived from the Moderate Resolution Imaging Spectroradiometer (MODIS, product MOD13C2.005) [*Huete et al*., 2002] and four data sets derived from the advanced very high resolution radiometer (AVHRR) (known respectively as PAL [*Agbu and James*, 1994]; FASIR [*Los et al*., 2000]; LTDR (version 3) [*Pedelty et al*., 2007]; and GIMMS [*Tucker et al*., 2005]). These time series were blended after linear adjustment using the MODIS NDVI as the reference [*Beck et al*., 2011; see supporting information for details]. The AWRA model includes a simple model to predict vegetation phenology and water use in response to soil water availability. Remotely sensed vegetation data were deliberately not assimilated into the AWRA system for this application: our motivation for including the model estimates is that they will be exclusively climate driven; whereas by contrast observed vegetation dynamics may also have been affected by other processes not necessarily drought related (see section 4). Daily time series of rainfall, radiation, and minimum and maximum temperature are input to the model, and therefore trends in these variables are considered; the influence of atmospheric CO_2 concentration is not considered. The model separately estimates transpiration and several evaporation components (rainfall interception loss, soil evaporation, open water evaporation, evaporation from groundwater saturated areas) and does this separately for areas covered by seasonal and perennial vegetation. We estimated crop water use as the transpiration of seasonal vegetation simulated by the model.

[34] Monthly time series of crop growth indicators averaged across all wheat-growing areas were calculated. For the NDVI products, it was investigated whether the various original and blended time series had different trends. For the blended data set, this was done by assessing any trend in the residuals between the original and blended data set. This was done to reduce the effect of interannual variability

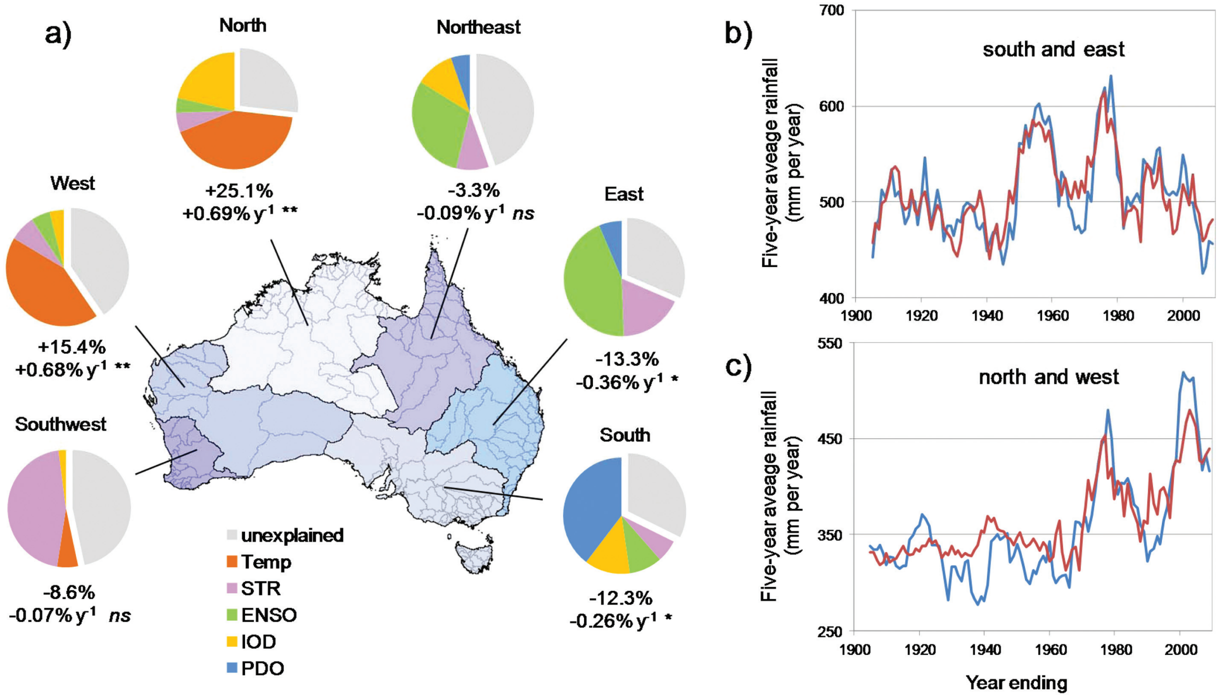

Figure 2. (a) Map of the rainfall regions and fraction of variance in rainfall patterns explained by different phenomena. Also shown are the 2001–2009 rainfall anomaly (in % of 1900–2000 averages) and linear 1950–2009 trend (in % per year). Symbol indicates significance level: ns = not significant; $^{*}P < 0.1$; $^{**}P < 0.01$). (b) Observed 5 year average rainfall (1900–2010) over south and east Australia combined (blue) and values from a regression model (red) based on indices of the phenomena shown in Figure 2a. (c) Same but for north and west Australia combined.

on the calculated trends, since different data sets were available for different periods.

[35] We fitted a simple multiplicative model estimating annual wheat yields (Y, tonnes per hectare) as the product of a time-invariant prediction of yield (Y_0) based on each of the three crop growth indicators (x) and a linearly increasing term ε that represents the effect of increasing conversion efficiency on the relationship between Y_0 and actual yield Y:

$$Y = \varepsilon Y_0 = (1 + kt)(ax + b), \quad (5)$$

where t is the number of years since the 1977/1978 financial year (starting July in Australia), and k, a, and b are empirical coefficients. The impact of the drought on yield was estimated using each of the crop growth indicators by inserting the predrought average value of the indicator and $t = 28$ (representing 2005/2006; the middle of the drought) into the fitted model. This produced an estimate of potential yield given predrought climate conditions. Actual yields were compared to these values to estimate the drought impact. The resulting impact on total production was estimated by multiplying with cropped area. This may underestimate the influence of the drought on production, because cropped areas also decreased during the drought years 2002/2003 and 2006/2007, mainly because planting decisions were to some extent influenced by the drought.

2.5. Economic and Social Drought Impacts

[36] A comprehensive study of the propagation of the impacts of the Millennium Drought on the Australian economy and society has not yet been undertaken. We did not have the necessary expertise or access to economic and social data to perform new analysis. Instead, we reviewed published studies on the economic and social impacts to obtain, at least in a conceptual sense, a more comprehensive picture of the way in which the (bio-)physical drought impacts propagated through the economy and society.

3. Results

3.1. Causes of the Meteorological Drought

[37] Six rainfall regions were distinguished following cluster analysis based on correlation between 1900 and 2009 annual rainfall patterns in 245 river basins (Figure 2). Optimal regression models that used up to four predictors were derived using 5 year rolling average time series of regional rainfall and candidate predictors. It is emphasized that this produced statistical results only, which need to be interpreted using climate process knowledge (see section 4).

[38] Three to four phenomena could explain (in a statistical sense) most of the variance in 5-year rolling average patterns (53%–73%; Figure 2; for details see Table 2 in the supporting information). An ENSO index (winter Nino3.4) explained 44% of variance in east Australia, with some of the residual variance explained by STR (18%) and PDO (6%). In south Australia, PDO explained 40% of the observed variance, with some of the remaining variance explained by IOD (13%), ENSO (9%), and STR (6%). In southwest Australia, STR explained 45% of variance, with smaller parts explained by global temperature (6%) and

Table 1. Estimated Contributions of Each of the Phenomena to 2001–2009 Rainfall Anomalies in Those Regions Experiencing Below-Average Rainfall[a]

Region	GMT (%)	STR (%)	ENSO (%)	IOD (%)	PDO (%)	Unexpl. (%)	Total %	Total mm/yr
Northeast	_	4.8	−8.2	−1.6	−0.8	+2.6	−3.3	−17
Southwest	−4.7	−4.0	_	+0.4	_	−0.3	−8.6	−34
East	_	−1.7	−8.1	_	−0.7	−1.8	−12.3	−66
South	_	+2.7	−3.2	−1.7	−1.7	−9.5	−13.3	−50

[a]Total anomaly is difference between 2001–2009 and 1900–2000 mean rainfall (%).

IOD (2%). The remaining regions did not experience a drought, but it is noted that in north and west Australia, GMT explained 42–43% of variance in rainfall (Figure 2; but see supporting information for caveats).

[39] Combining the regression model parameters with predictor anomalies for 2001–2009, the contributions of different drivers to the meteorological drought were estimated (Table 1). The ENSO appeared to explain most of the 2001–2009 rainfall deficit in east Australia (−8.1 out of −12.3%) and a smaller part in south Australia (−3.2 of −13.3%; Table 1), while smaller contributions were made by PDO in both regions (−0.7% and −1.7%, respectively) and, in south Australia only, IOD (−1.7%). STR was estimated to contribute a −1.7% reduction in east Australia, but a counterintuitive +2.7% in south Australia. In northeast Australia, ENSO was also estimated as the main cause of the small rainfall deficit but was counteracted by a seemingly positive influence from STR. In southwest Australia, GMT (−4.7%) and STR (−4.0%) together appeared to explain the −8.6% rainfall deficit.

[40] Statistically significant ($P < 0.1$) drying trends (1950–2009) in annual rainfall were found for east (−0.36% per year) and south Australia (−0.26% per year) (Figure 2). Combining the regression model parameters with 1950–2009 trends in predictor variables produced estimates of their potential contribution (Table 3 in the supporting information). Overall, results were similar to the estimation of drought contribution. In east Australia, drying appeared due to trends in ENSO, STR, and PDO in approximately similar parts. In south Australia, PDO appeared to explain a large part of the observed rainfall decline, with smaller contributions from ENSO and IOD. Strong ($P < 0.01$) wetting trends were calculated for north (+0.69% per year) and west Australia (+0.68% per year) and were correlated to a similar trend in global temperature. No significant trend was calculated for southwest and northeast Australia.

3.2. Hydrological Drought Impacts

[41] We analyzed streamflow data from the headwater catchments that were located in the three rainfall regions affected by the drought (East, South, and Southwest Australia, $N = 126$) and found that the median rainfall reduction during the drought (11%) was amplified 4.1 times in streamflow (−46%; Figure 3). The simple nonlinear model was fitted to 30–87 (mean 40) years of observed data and could explain 35–91% (mean 73%) of the observed variance in annual streamflow. It predicted a 25% decrease in streamflow, which equates to an amplification of 2.21 times relative rainfall decrease.

[42] The AWRA process model suggested a 37% reduction or 3.19 times amplification. Figure 3b demonstrates that for the driest pre-2001 years, the models predict streamflow declines that are much closer to observed declines, although the AWRA process model predicts a slightly lesser decline than observed (54% versus 62%). These results suggest that there has been a cumulative drying effect on streamflow during the prolonged 2001–2009 drought.

3.3. Ecological Drought Impacts

[43] During the drought years, the average observed flows were 2445 gigalitres (GL) per year, whereas the reconstructed unimpeded flows were 7568 GL per year (Figure 4a). Average reconstructed unimpeded flows for the period 1900–2000 were 13,830 GL per year. It follows that 2001–2006 actual river flows were 82% less (2445/13,830) than estimated long-term average flows without regulation (i.e., impoundment, release and extraction of flows). This 82% represents the combined impacts of drought and regulation. By comparison, flows during the drought would have been expected to be reduced by 45% (7568/13,830) in the

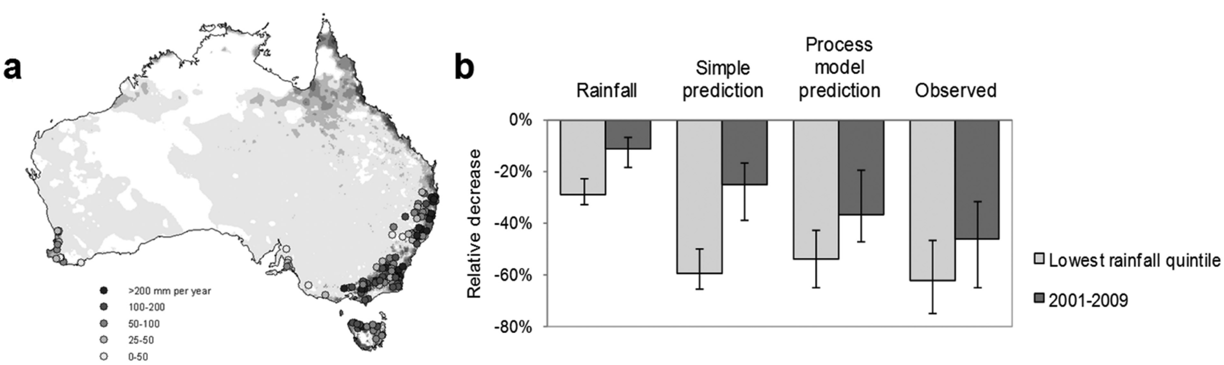

Figure 3. (a) Map showing the model-estimated reduction in streamflow generation during the drought, and the reductions observed in 126 upland catchments used in the analysis; (b) Comparison of relative decreases in rainfall and estimated and observed streamflow in the 126 catchments for the driest 20% years occurring before 2001 (light shaded), and the average flows during the 2001–2009 drought (dark shaded). Error bars show interquartile range.

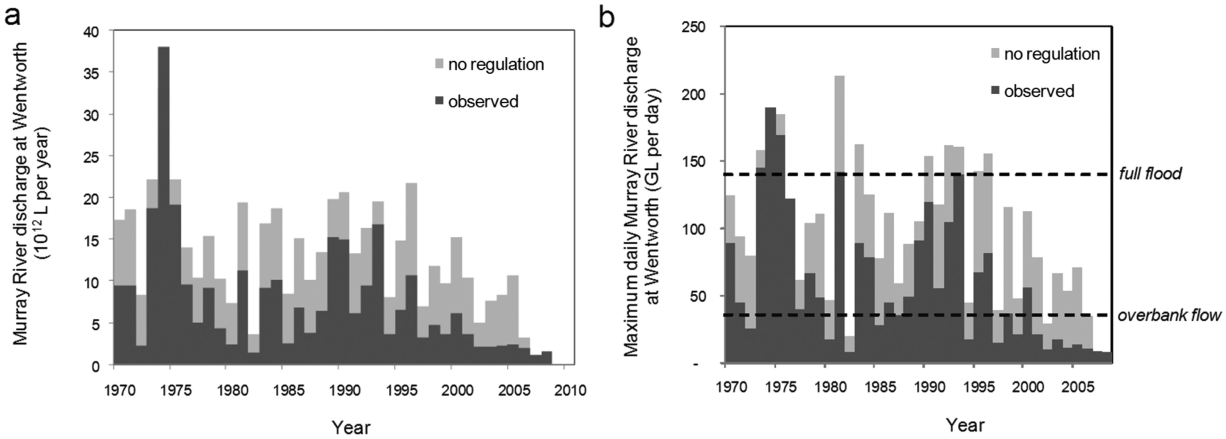

Figure 4. (a) Annual total flow and (b) annual maximum daily flow in the Murray River at Wentworth (see Figure 1b for location) as observed and as estimated to have occurred in the absence of river regulation.

absence of any regulation. In other words, low inflows are estimated to be responsible for 45% of the decrease, and regulation for the remaining 37% reduction. Given the basinwide rainfall decline of 18.4%, this implies an amplification of 4.47 times with and 2.46 times without regulation, respectively; apparently, river regulation amplified "natural" flow reductions by another 1.8 times. The annual maximum observed daily flows in most years was considerably lower than was estimated to have occurred under unimpeded conditions (Figure 4b).

3.4. Agricultural Drought Impacts

[44] Rice and cotton are two important irrigated annual crops and are grown predominantly in the MDB when there is sufficient water stored in the supplying reservoirs. Total MDB water diversions fell from an average 11 km^3/yr (1993–2002) to 8 km^3/yr in 2002/2003 and 4 km^3/yr in 2008/2009. The consequences for rice and cotton production were considerable: between 2002 and 2009 irrigated rice and cotton production fell by 99% and 84%, respectively (Figure 5) [*ABS*, 2011], despite simultaneous increases in WUE.

[45] Dryland wheat production increased during the drought years in terms of production volume, but only because a −12% yield per unit area decline (comparing drought and predrought years) was compensated by a +22% increase in cropping area (Figure 6). The three tested indicators of wheat production could each explain 66%–68% of the recorded variations in crop yields, but crop water use and VOD required an annual 1.3% increase in WUE to be taken into account, whereas NDVI did not (Figure 6, Table 2). Using each of the three indicators, it was estimated that yields during the drought (July 2002–June 2009) were 18%–22% lower than would have been achieved under average conditions; an amplification of 1.5–1.7 times the rainfall decline (Figure 6, Table 3).

4. Discussion

4.1. Causes of the Meteorological Drought

[46] The objective of the precipitation data analysis was to quantify the potential contribution of known climate phenomena to the Millennium Drought. We did not use prior knowledge to preselect from the full complement of candidate predictor variables, as this would have introduced a greater degree of subjectivity. An obvious downside is that it can cause counterintuitive analysis results. Potential causes of erroneous variable selection include spurious correlation and interactions between climate phenomena. To mitigate these uncertainties, we interpreted our statistical results along with evidence from published climate process studies and data on covariance between

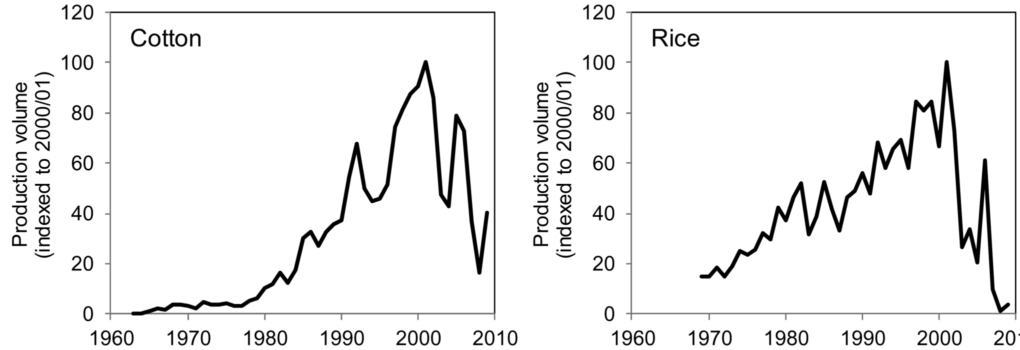

Figure 5. Production of two major irrigated annual crops in the MDB [*ABS*, 2010].

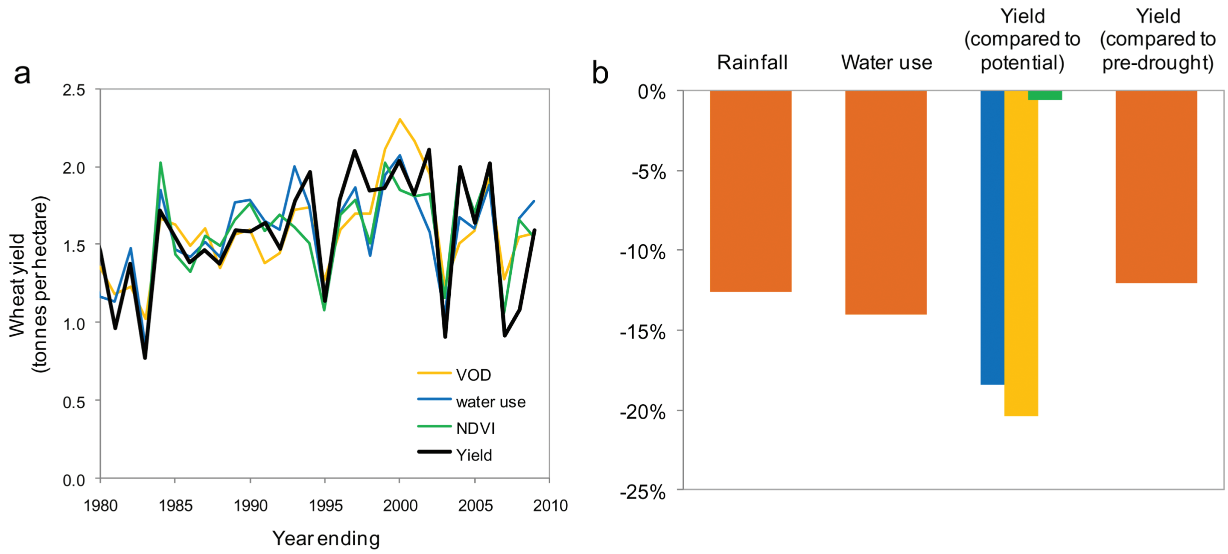

Figure 6. (a) Total Australian wheat production and predictions for the intensive cropping zone (Figure 1b) based on crop growth indicators, accounting for a long-term increase in conversion efficiency. (b) Estimated drought impact on rainfall, crop water use, and yield, as estimated from crop water use, VOD and NDVI (colors as in Figure 6a). Also shown is yield decline compared to pre-drought yields.

indices. A detailed discussion is provided in the supporting information, but the main points are summarized below.

[47] Statistically, ENSO explained 44% of the rainfall variance in east Australia, two thirds of the 2001–2009 rainfall deficit, and about a third of the 1950–2009 rainfall trend. It also explained most of the rainfall deficit in northeast Australia and a minor part of the variance, rainfall deficit, and long-term drying trend in south Australia. The importance of ENSO on rainfall along the eastern seaboard is well published, but its influence is normally considered strongest in spring in south Australia and summer in east Australia [*Risbey et al*., 2009]. However, in both regions, most of the rainfall deficit during 2001–2009 occurred in the cooler months (autumn and spring in east Australia, and autumn and winter in south Australia), whereas summer rainfall was above average [*CSIRO*, 2010]. This suggests that while the interannual ENSO influence may be strongest in the spring-summer season, its influence on the drought and on long-term trends may be stronger in winter. Alternatively, there may be a global warming signal embedded in the Nino3.4 index that was selected by the model.

[48] PDO seemed the strongest 5 year average rainfall predictor in south Australia, making an important contribution to the long-term rainfall decline and a small contribution to the 2001–2009 rainfall deficit. The importance of PDO as a low frequency influence has been described [*Power et al*., 1999], but its possible role in the decadal drying trend in south Australia has been less commented on. The estimated small contribution of PDO to the 2001–2009 rainfall deficit suggests that PDO was not a major factor in the Millennium Drought, however.

[49] The intensity and to a lesser extent location of the STR have been proposed as an important predictor of cool season rainfall in southwest and south Australia [*Hope et al*., 2010]. Our statistical results with regard to the influence of STR on rainfall in the southern half of Australia appeared partly contradictory. We hypothesize that this may have been due to covariance between the PDO and STR indices or indicative of a relationship both have with global warming [cf. *Timbal et al*., 2010], at least when averaged over 5 years (see supporting information for details).

[50] Previous studies on the importance of the IOD and SAM in the Millennium Drought have been contradictory (section 2.1). Our analysis provided some support for a role of IOD on the Millennium Drought in south Australia, but we were unable to identify any influence of SAM on the 2001–2009 drought or long-term trends.

[51] Overall, our results confirm that that ENSO was the most important driver of the Millennium Drought in east Australia and explained a small part of the rainfall deficit in south Australia. Our data analysis proved inconclusive with

Table 2. Parameters of the Simple Model to Explain Recorded Wheat Yields as a Function of Remotely Sensed Biomass (VOD) or Greenness (NDVI) or Model-Estimated Water Use[a]

	VOD	NDVI	Water Use
k	0.0125	−0.00031	0.0134
a	7.02	16.1	1.19
b	−1.88	−5.16	−0.441
SEE	0.22	0.22	0.21
R^2	0.66	0.66	0.68
N	31	28	32
R^2 (Y_0 only)	0.54	0.66	0.52

[a]Also listed are the standard error of estimate (SEE, in tonnes per hectare), the coefficient of correlation of the fitted model (R^2), the number of observations (N) and the R^2 that could be achieved if the first time-dependent model term was left out ($R^2(Y_0)$).

Table 3. Average Predrought and Drought Values for Hydrological and Agricultural Indicators

	Rainfall (mm/yr)	Water Use (mm/yr)	VOD	NDVI	Yield (t/ha/yr)	Area (Mha)	Production (Mt/yr)
1982/1983–2000/2001 average	553	553	0.47	0.42	1.65	10.3	17.1
2001/2002–2008/2009 average	483	475	0.42	0.42	1.45	12.5	18.4
relative difference	−12.6%	−14.0%	−9.2%	−0.1%	−12.0%	21.6%	7.7%

regard to the main causes of the drought in south Australia. Correct attribution is particularly important to anticipate any systematic changes in future drought characteristics. Different phenomena are anticipated to be affected by global climate change to different degrees. For example, STR shows a long-term trend consistent with changes in the Hadley circulation expected from global warming [*Hu et al.*, 2011, and references therein; *Kent et al.*, 2011; *Nicholls*, 2006]. On that basis, global warming has been hypothesized as a factor contributing to the drought. The sensitivity of other drivers to global warming is much more tenuous. There appears little agreement among global climate models about the influence of global warming on ENSO [*Van Oldenborgh et al.*, 2005], even though *Power and Smith* [2007] noted that many existing ENSO indices attained unprecedented values during the period 1977–2006. Similarly, a mechanism by which global climate change influences PDO has so far not been established. Regardless, the apparent importance of PDO as a low-frequency driver of decadal precipitation trends suggests a potential source for climate nonstationarity that warrants further research in its own right [cf. *Speer et al.*, 2011].

4.2. Hydrological Drought Impacts

[52] A simple statistical model that ignores temporal correlation or subannual rainfall patterns predicted an amplification of rainfall deficit in streamflow of 2.2 times (Figure 2b) based on the streamflow data from the 126 catchments in east, south, and southwest Australia. One reason for this amplification is likely to be that autumn and to a lesser extent winter rainfall were reduced considerably more than rainfall during the other seasons [*Chiew et al.*, 2011; *Potter and Chiew*, 2011]. The daily time step model considered such weather patterns as well as catchment storage dynamics and predicted an amplification of 3.2 times. This still leaves a 1.3 times amplification unexplained.

[53] In southwest Australia, greater than expected reductions in catchment streamflow during a sequence of dry years were associated with the decline of groundwater tables below the river streambed, causing a loss in hydrological connectivity and resilience [*Petrone et al.*, 2010]. TWS observations by the GRACE satellite measurements [*Tapley et al.*, 2004] suggest that increasing water-storage deficits occurred across southern Australia during the drought and were not fully reproduced by the AWRA model (Figure 7). This unexplained trend has been attributed to groundwater depletion [*Leblanc et al.*, 2012, 2009; *Van Dijk et al.*, 2011]. Total storage did not recover until the unusually wet period in early 2010 (Figure 7) suggesting that catchment function required above-average rainfall conditions to be restored. This has implications for the accumulative impact of future droughts on streamflow generation and subsequent recovery of catchment function; it suggests that drought conditions may linger until there is a particularly wet period.

4.3. Propagation Through the Hydrological Cycle

[54] Understanding and describing droughts is complicated by the way in which impacts propagate through the water cycle. For the MDB, time series of several relevant observation-based estimates were available to illustrate this. Already introduced were precipitation, remotely sensed total terrestrial water storage, and downstream Murray River flows. Additional available data include estimates of total storage in the basin's public reservoirs (data from *Leblanc et al.* [2012]) and in the combined groundwater stores (using groundwater level data and methods in *Tregoning et al.* [2012]).

[55] The propagation of the drought throughout the hydrological cycle caused observable differences in the timing of the worst drought impacts by up to several years (Figure 8). For example, 6 month average precipitation anomalies reached a minimum in January 2003 and a second, slightly less low value in January 2007. By contrast, the first total water storage minimum coincided with the first precipitation minimum but recovered rapidly afterward, whereas the second minimum occurred in October 2009; more than 2 years after the second precipitation minimum. Combined public water storage achieved a temporary minimum in April 2003 before dropping further until May 2007. Downstream peak flows in the Murray River remained low throughout the drought, although data were missing during most of 2008 and 2009; understood to be a result of gauging problems due to the unusually low flows. Finally, groundwater storage showed a different pattern again, remaining in apparent dynamic equilibrium until the end of 2006 and then steadily decreasing until the

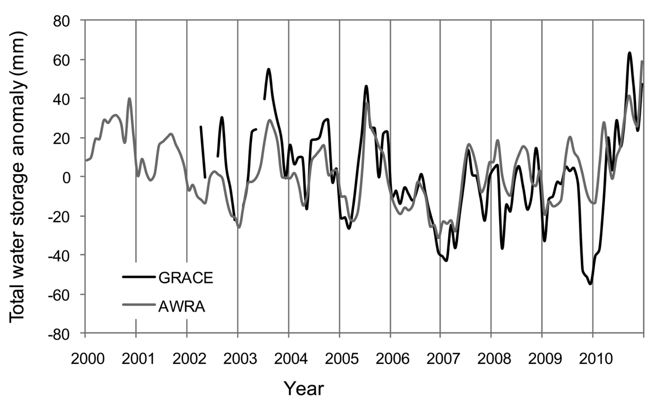

Figure 7. Satellite-observed (black) and model-estimated (gray) total water storage over regions east, south, and southwest (cf. Figure 2a) combined. Data shown is 3 month rolling average for figure clarity.

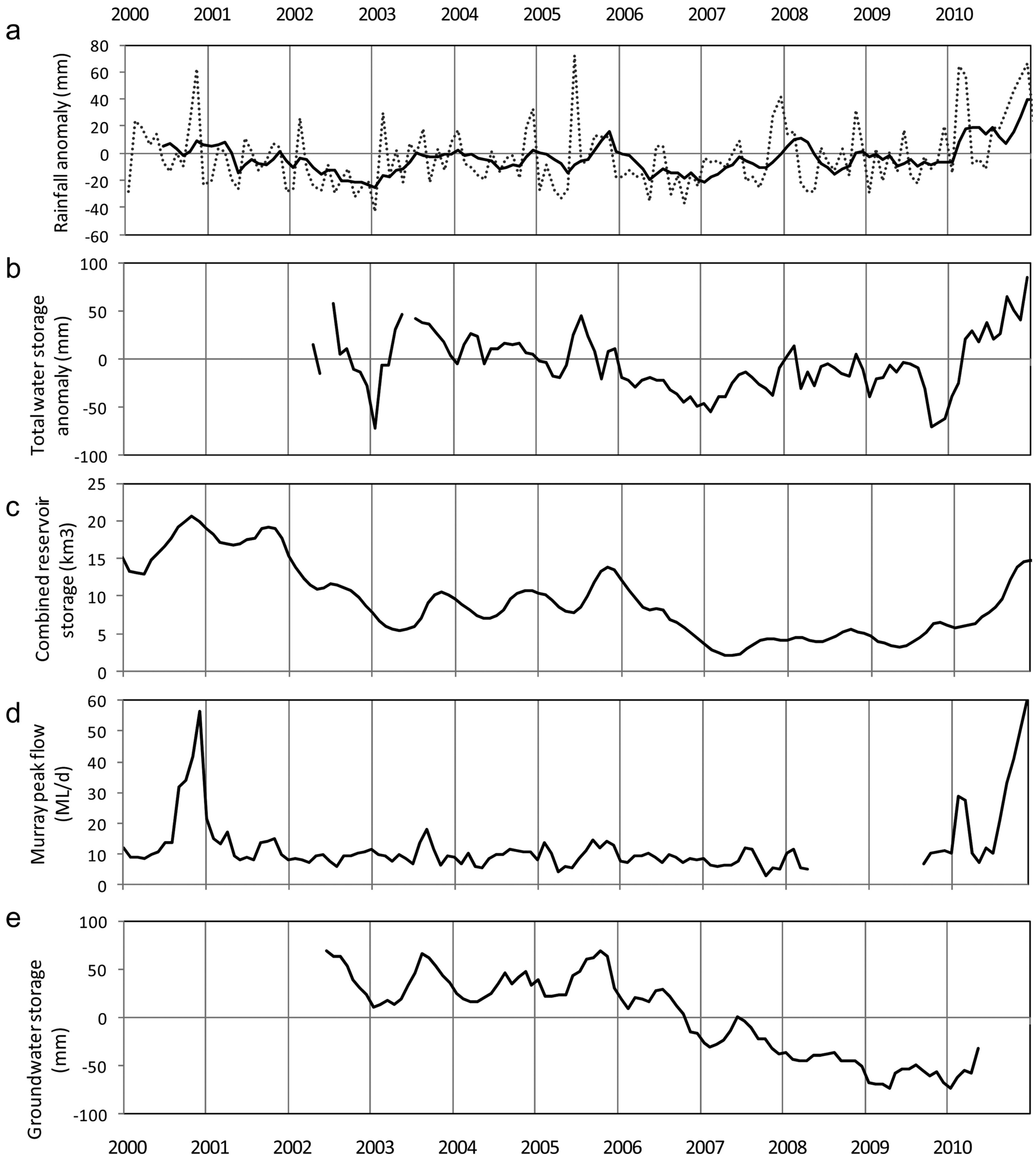

Figure 8. Propagation of the meteorological drought through the hydrological cycle in the MDB: (a) monthly rainfall anomalies (dotted) and 6 month running average (solid); (b) GRACE satellite-observed average monthly terrestrial water storage; (c) combined storage in public reservoirs; (d) daily peak flow by for each month in the Murray River at Wentworth; and (e) estimated MDB groundwater storage.

beginning of 2010 (individual bore data suggest that widespread recovery occurred after this). The varying response of different hydrological variables can be attributed to a combination of natural hydrological processes (e.g., slow groundwater losses to vegetation water uptake and capillary rise) and human influences (e.g., reservoir operation and river water diversion) and illustrate the potentially complex interactions during multiyear hydrological droughts. This complexity affects our ability understand, describe, monitor, and explain the hydrological impacts of long droughts.

[56] While our case study has some unique local features, it is obvious that a single drought index can never be expected to describe the multitude of impacts during multiyear droughts. A wider set of drought indicators is needed, going beyond precipitation and (shallow) soil moisture and describing gradually accumulating impacts. Ultimately, human and instrumental observation networks on the ground probably remain the only reliable way to monitor drought impacts, but there are many opportunities to move beyond the current generation of simplistic rainfall-based drought indicators and develop a more sophisticated

drought monitoring capability. As a case in point, satellite and biophysical model data identical or similar to those used in the current case study are all available with global coverage. International collaborative initiatives are underway to develop these data sources into useful information services [e.g., *Pozzi et al*., 2013].

4.4. Ecological Impacts

[57] The amplified impact of the drought on riverine ecosystems was caused by a combination of the natural amplification that occurs moving down a river system (e.g., due to evaporative and riparian losses on the way) exacerbated considerably by extractions and the operation of river infrastructure to supply water users. River regulation was identified as the leading cause for the strongly reduced frequency of medium size floods and associated decline in health of the vast riparian River Red Gum (*Eucalyptus camaldulensis*) forests even before the onset of the drought [*Davies et al*., 2008; *Gehrke et al*., 2006]. Our results confirm that in the absence of regulation, at least partial flooding would still have occurred during the drought.

[58] Comparing observed flow patterns with modeled scenarios, we estimate that without river regulation the basinwide 2001–2006 rainfall deficit of 18% would have led to a 45% reduction in total flow (an amplification of 2.46 times), whereas the observed reduction was 82% (4.46 times). It follows that river management almost doubled the reduction of average river flows. It also caused an absence of flood events (Figure 4b). The river flow range over which increasingly large areas of floodplain are inundated has been estimated at 36.7–140 GL per day [*CSIRO*, 2008b]. Comparing this to modeled and observed maximum flows shows that, prior to 2010, development increased the number of years without a major flood event from 15 to 18 years, and was also responsible for the absence of smaller flood events since 2000 (Figure 4b).

[59] Inevitably, there is some uncertainty in modeling the hypothetical unregulated flows. The river model uses observed data on tributary river inflow and therefore the biases in catchment models estimating streamflow generation (section 4.2) are less of a concern. There are additional sources of potential bias however, particular with regard to the estimation of river losses (e.g., to groundwater, off-channel wetlands, and floodplains). As part of a previous implementation of the same model, a detailed analysis of model performance against river flows observed before and during the drought was performed [*Van Dijk et al*., 2008]. A number of instances of river model bias were identified, but most affected low flows rather than peak or total flows. The results obtained here would appear to be fairly robust therefore.

[60] We did not quantify drought impacts on dryland ecosystems (other than agricultural crops) but they were widespread (cf. Figure 1a). Increased tree mortality has been observed well away from rivers [*Semple et al*., 2010] and fire activity was strongly increased during the drought with large tracts of native and plantation forest being burnt. Further research would be needed to quantify the immediate and long-term impacts of the Millennium Drought on these ecosystems.

4.5. Agricultural Drought Impacts

[61] The observed reduction in irrigated agriculture during the drought can be attributed directly to the decline in river inflows and consequent declines in reservoir storage and released volumes. Water sharing rules meant that initially, reduced water allocations mainly affected the irrigation of annual crops such as rice and cotton (Figure 5), as well as irrigated pasture (for which production impacts are not readily assessed using sector production data). As the drought intensified, however, crops relying on more secure water rights ultimately were also affected. For example, the production of summer-bearing oranges—an important perennial crop under irrigation—was 32% lower in 2003–2007 than during 1999–2002 (data from Citrus Australia).

[62] In dryland agriculture, rainfall declines were amplified 1.5–1.7 times in wheat yield declines but the impact on long-term trends was counteracted by increased crop WUE. The three indicators of dryland wheat production all had interannual patterns that were very similar to those observed in wheat yields, but long-term trends varied. On the basis of modeling, we expected a reduction of NDVI in line with reduced rainfall, but the observations show no such response to rainfall decrease. Our interpretation is that NDVI observations embody the long-term increase in WUE, whereas the other two indices do not. To test this, we compared the monthly time series of blended satellite NDVI with NDVI estimated from AWRA model output. NDVI is estimated using a linear relationship with modeled canopy cover that was calibrated against MODIS NDVI data for 2000–2006; AWRA canopy cover and NDVI estimates have been evaluated previously against satellite-observed vegetation products, showing good agreement for annual cropping regions [*Van Dijk and Warren*, 2010]. The observed and modeled NDVI are shown for monthly and annual data in Figures 9a and 9b, respectively. Despite good correlation ($R^2 = 0.79$), there is a clear difference in linear trends. Keeping in mind that the model NDVI was calibrated for MODIS NDVI (2000 onward), it can be concluded that the model estimated NDVI reduced over time (due to reduced rainfall), whereas the observations show no such response. Two explanations for this phenomenon may be considered:

[63] First, the lacking trend in AVHRR NDVI might have been an artifact of the satellite data or their processing. The original AVHRR NDVI products were produced using different approaches and assumptions to correct for the lack of onboard calibration of the AVHRR instrument [*Beck et al*., 2011]. If this explanation was correct, some of the products might be expected to show a declining trend. Table 4 shows that all data sets show similar (small) positive trends. Thus, while we cannot completely exclude this explanation, the evidence appears to be against it.

[64] Second, the AWRA model may have wrongly predicted a negative trend. Conceptually, if the relationship between water availability and vegetation density is stationary, we would expect a reduction in vegetation growth if water availability diminishes in an already water limited environment. This is indeed what the model predicts; there was a negative rainfall trend over the analysis period.

[65] In reality, there are reasons to doubt a constant relationship between water availability and vegetation density,

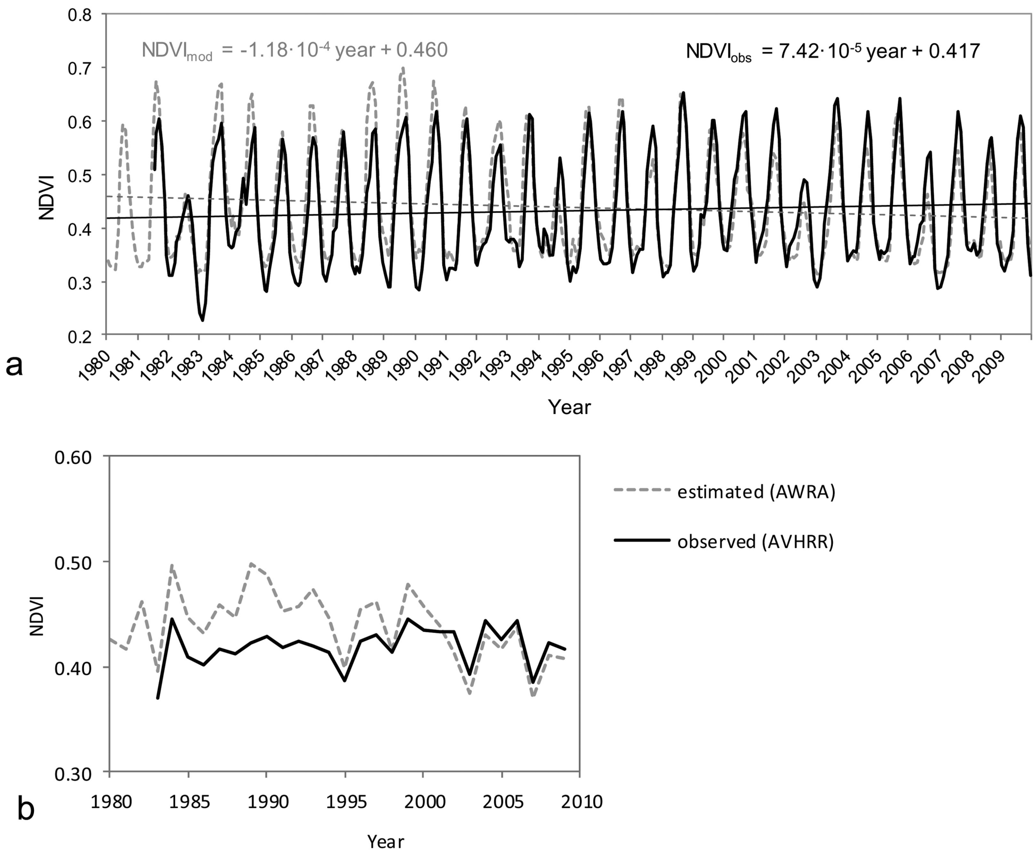

Figure 9. (a) Monthly and (b) annual time series annual blended NDVI for the intensive cropping zone (Figure 1b) and NDVI estimated from modeled canopy cover (years ending June).

particularly for crops. Such a constant relationship requires that the conversion efficiency (WUE) from transpiration via carbon assimilation to produced crop yield is constant overall. Instead, long-term increases in conversion efficiency are known to have occurred; due to crop breeding, increased nutrient inputs and improved cropping practices, potentially enhanced by anthropogenic CO_2 fertilization [*Turner and Asseng*, 2005]. Conversion of vegetation (within what was designated as cropping area in Figure 1b) to wheat crop may also result in greater NDVI per unit VOD or water use, depending on prior vegetation. Fertilization with anthropogenic atmospheric CO_2 could have further contributed to increasing WUE: average concentrations during the drought (2002–2008) were 7.1% higher than on average during the period 1980–2001. Over the period 1981–2007, global atmospheric CO_2 concentrations have grown at 0.46% per year, which in a water limited environment could theoretically be expected to result in corresponding increase in WUE, if not necessarily expressed in increased growth [*Peñuelas et al.*, 2011]. Over the same period, model estimated crop water use decreased by 0.44% per year (−2.4 mm per year, period average 540 mm) due to rainfall patterns. Overall, it appears plausible and indeed likely that WUE has increased over time, but our data do not provide conclusive evidence for a CO_2 fertilization effect in addition to agricultural improvements.

4.6. Economic and Social Drought Impacts

[66] The contribution of agricultural production to Australia's economy fell from 2.9% (financial years ending 1997–2002) to 2.4% of GDP (2003–2009), contributing only 2.1% in the peak drought years ending in 2003 and 2007 [*ABS*, 2011]. This 16% difference in GDP contribution is 1.25 times the relative rainfall difference of 13% between the two periods. Such a calculation is obviously a simplified one; for example, the drought impacts are superimposed on a long-term slow decreasing trend in the overall importance of agriculture for Australia's GDP. Other studies estimating the impact of the drought are restricted to one of the drought years: *Horridge et al.* [2005] estimated that the drought lowered national GDP in 2002 by 1.6%, whereas the *Reserve Bank of Australia (RBA)* [2006] estimated that the 2006–2007 dry year reduced GDP by almost 1%.

[67] Arguments can be and have been raised against GDP as an appropriate measure of economic health. For example, while contributing less than 3% to GDP, agriculture represents a fifth of Australia's export value and is the primary source of income for many rural communities inhabiting a large part of the country. In the drought-affected areas the economic impacts were obviously larger than at national level: for the worst affected regions within the MDB, *Horridge et al.* [2005] estimated that gross regional product (GRP) in 2002 was reduced by more than

Table 4. Trend Calculated for the Different AVHRR Derived and Blended NDVI Time Series for 1982–1999[a]

Product	Trend (Per Year)
GIMMS	+0.00158
LTDR	+0.00207
FASIR	+0.00160
PAL	+0.00180
Blended	+0.00156

[a]Note that the available months vary somewhat between data sets.

15% and employment by 3%, and for the Murray River region *Wittwer and Griffith* [2011] estimated that during 2006–2009 about 6000 jobs were lost.

[68] The earlier studies focused on economic impacts through agriculture, but the drought also affected other sectors. Forestry is one example: between 2003 and 2009 more than 57,000 ha of planted forests were lost in southeast Australia, representing about 3% of the national plantation estate [*Stewart*, 2009]. Tourism, of similar importance to agriculture in terms of GDP, export value, and employment, is another example. National level estimates of the impact of the drought do not appear to exist, but for the Murray River region alone, it was estimated that the drought reduced tourism GRP by 5% in 2008 (equivalent to 0.7% of the GDP contribution of tourism [*ABS*, 2011]) with 600 jobs being lost [*Tourism Research Australia (TRA)*, 2010]. Virtually all economic activities will have been affected to some degree by the reduced availability and greater costs of utilities. For water, this includes the direct impacts of household and industrial water restrictions and costs, and the indirect costs from infrastructure investments (e.g., desalination plants). Electricity prices were also driven up by the drought, particularly in 2007, when surface water availability reduced hydroelectric and coal power generation and hot conditions increased demand [*Plumb and Davis*, 2010]. The overall impact of these factors on the economy does not appear to have been estimated, however.

[69] Reports on the social impacts of the drought paint a picture of rural communities suffering unemployment and loss of household income, local businesses and services, recreational opportunities, and social cohesion [e.g., *Drought Policy Review Expert Social Panel*, 2008, and references therein]. Combined with the harsh weather and desiccated landscape, they increased psychological health problems [e.g., depression, substance abuse, and suicide; *Nicholls et al*., 2006]; the impacts on physical health do not appear to have been studied.

[70] A key challenge for both economic and social drought impact studies is to identify and control for the often rather wide range of other drivers beyond the drought. Important among these is the undercurrent of steady decline that many of Australia's rural communities have been experiencing over recent decades.

[71] The institutional and political impacts of the drought may be considered a subset of social impacts. They are partially reviewed by *Leblanc et al*. [2012] (for the case of water management policy) and the *Productivity Commission* [2009] (for the case of government drought policy). It is clear that the drought catalyzed a number of permanent reforms in water and drought policy and institutional arrangements. Equally, however, it is not difficult to find evidence that the sudden end of the drought, combined with unfavorable political factors (e.g., budget pressures and polarized federal-state relations) has slowed down progress on remaining, often more contested and uncertain decisions (e.g., environmental flow provision and its merits).

5. Synthesis

[72] Although ENSO was found to play a role in the Millennium Drought, we could not unambiguously identify the other drivers of the meteorological drought. This is perhaps not surprising given the challenges in attribution and the contradictory results of previous studies. In addition to this attribution challenge, another problem remains that for many of the candidate drivers the likely future trajectory and the way it may be influenced by global warming cannot currently be predicted with confidence. Therefore, we are left unable to anticipate whether future droughts will likely be systematically different from past ones (although with the noteworthy exception that they can be expected to be accompanied by increasingly high temperatures due to global warming). The synoptic conditions during the drought (i.e., the STR) were consistent with the poleward expansion of the Hadley circulation expected under global warming, which should be a cause for concern and further investigation. Other research priorities would appear to be the potentially changing behavior of ENSO under global warming, and the trajectory of future PDO conditions.

[73] We demonstrated that the propagation of meteorological drought conditions through the hydrological cycle during this multiyear drought involved several nonlinear responses and accumulating impacts. As a result, the timing and duration of impacts on soil moisture, river flows, reservoir storage, and groundwater levels varied by months to years. It follows that simple rainfall-based indicators should not be relied upon to characterize drought. Fortunately, a wider set of observation-based drought measures has become available from improved remote sensing and model technologies and can be used in future droughts.

[74] Total storage did not recover until the unusually wet period in early 2010, suggesting that catchment function required above-average rainfall conditions to be restored. This has implications for the accumulative impact of future droughts on streamflow generation and subsequent recovery of catchment function. It suggests that drought conditions linger until there is a particularly wet period, supporting social perceptions about drought commonly found in rural Australia [*McKernan*, 2005].

[75] Wheat production continued to increase during the drought only because cropped area increased and because water deficiencies were partly mitigated by ongoing increases in crop WUE (including a potential CO_2 fertilization effect). This emphasizes that there are ways by which the impacts of future droughts can be mitigated. However, it would seem an inevitable consequence that total wheat production has become more sensitive to drought in terms of total production volume. This is likely to contribute to volatility in a global wheat market that appears increasingly sensitive to variations in supply.

[76] River regulation clearly provided a highly effective means to manipulate and distribute the impacts of drought

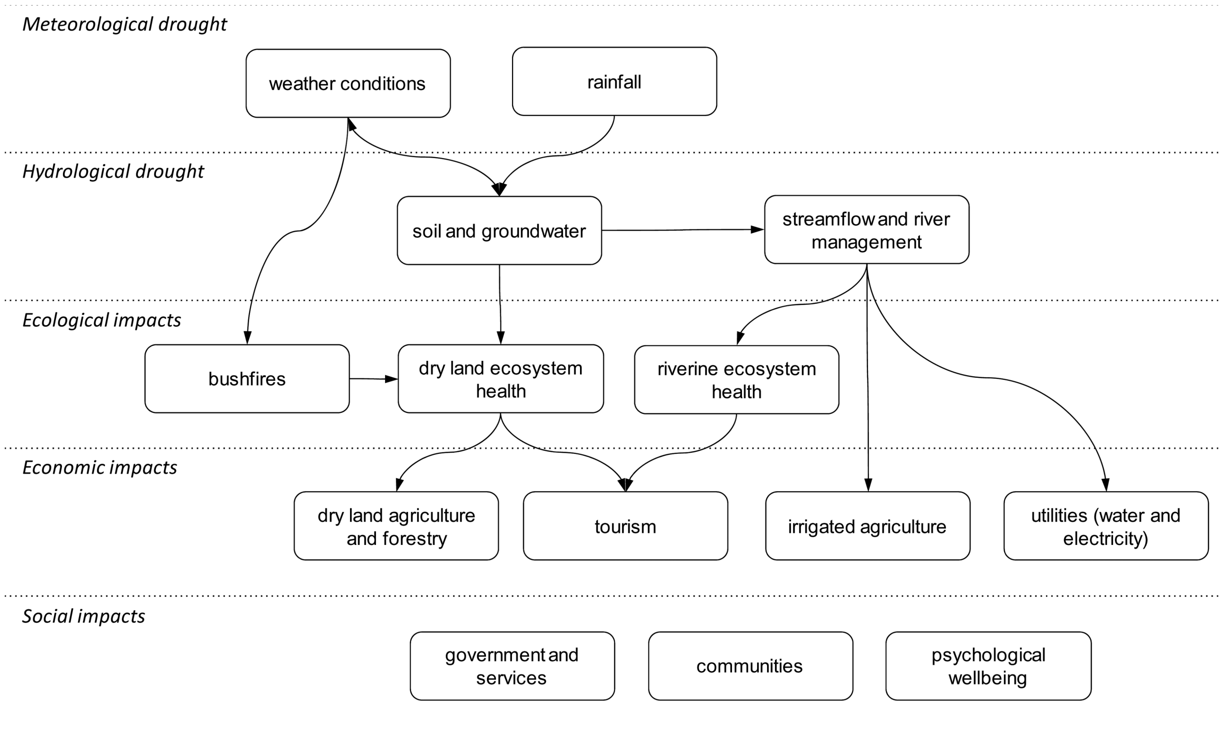

Figure 10. Diagram illustrating how the meteorological drought propagated through the hydrological cycle and had ecological, economic, and social impacts. The diagram is not complete, showing only key impacts and dominant links identified and discussed in the text (e.g., social impacts are understood to be the combined result of several of the impacts shown, but dominant pathways could not be identified).

on riverine ecosystems and communities, mitigating the impacts for some by exacerbating them for others. Water sharing rules and trading favored users reliant on continued supply, including irrigation of perennial high value crops and water utilities, while lower security water users and riverine ecosystems wore the consequences [*CSIRO*, 2008a; *Van Dijk et al*., 2008]. The MDB surface water system appears fundamentally overdeveloped and adaptation appears no longer possible without incurring considerable costs. *Williams* [2003] argues that current water management is based on the optimistic myth that it is possible to "drought-proof" Australia's agriculture and advocates instead that Australia be "myth-proofed." We would include, as part of this myth, the notion that Australia's riverine ecosystems can be restored without incisive changes in water extraction and regulation. The current political process reflects this dilemma. An added complication is that the negative outcomes (e.g., less and more expensive irrigation water resources and associated community impacts) are more predictable and more acutely felt than the intended positive outcomes of increasing the resilience of riverine ecosystems and communities.

[77] As much as the impacts of the meteorological drought on water resources, ecosystems and agricultural production were confounded, the more diffuse impacts on economy and society appeared even more complex and hard to quantify. There appears to be a general lack of systematic studies categorizing, quantifying and attributing the economic and social impacts of drought and the dominant causative processes involved. For example, most studies appear to focus on agricultural production and rural farming communities, whereas some of the examples discussed illustrate that the drought impacts went well beyond these. The conceptual diagram in Figure 10 illustrates this lack of knowledge: apart from its impact via crop production, we were unable to identify the main pathways by which the meteorological and hydrological drought impacted economic and social wellbeing. This would seem a major gap in our understanding that makes it unlikely that future droughts can be managed more successfully than historic ones. Further studies, arguably best working backwards from the main impacts experienced, would seem essential. A similar argument holds for the health of dryland ecosystems (inc. groundwater dependent ecosystems) and, to a perhaps slightly lesser extent, riverine ecosystems.

[78] Our results illustrate the complex nature of multiyear droughts, when compared to seasonal drought. The long duration provides much opportunity for cumulative impacts, interactions and feedbacks and complex interactions with other changeable external factors to occur. Severe droughts are by definition rare events and each historic multiyear drought has had different characteristics [*Verdon-Kidd and Kiem*, 2009b]. There appears to be a tendency for each drought to be perceived as "the worst on record" [*McKernan*, 2005]. Precisely because of the low frequency, the different nature of each drought, and the different dimensions of drought (extent, severity and duration) it is indeed likely that each new severe drought will have unique features, have unexpected impacts, and be "the worst on record" in some aspects. For the Millennium

Drought, some of the uniquely severe impacts appeared to have been "primed" by the relatively dry years before 2001, in combination with the rapidly increased level of urban and irrigation water resources use.

[79] Previous authors have noted a gradual change and broadening in public discourse in Australia, from considering drought primarily as a natural disaster to including an additional view that recognizes drought as a recurrent feature of the Australian climate and therefore a predictable risk [e.g., *Leadbeater*, 2007; *Stehlik*, 2005]. The latter view has been used to argue that drought risks should be anticipated and carried by those directly impacted. However, this presumes that our historic record is sufficiently long and that climate conditions are sufficiently stationary for such planning to occur. With each successive severe drought having unique features, with the presence of naturally unstable climate drivers (e.g., PDO), and with the specter of global climate change, this may prove to be an unrealistic expectation.

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