4. Climate Change and its Impacts: Current understanding, future directions

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Introduction

Global climate change is well documented through warming of the atmosphere and oceans, sea-level rise and changes in the cryosphere (the portions of the Earth's surface where water is in solid form) over the past few decades. Climate change is also occurring across the Murray–Darling Basin (MDB), as is evidenced by increasing temperatures. There is strong evidence that changes in greenhouse gas concentrations due to human activity are the dominant cause of the global warming that has taken place over the past half-century. Global warming is, in turn, causing changes to the whole *climate system*—the highly complex interaction between the atmosphere, oceans, water cycle, ice, snow and frozen ground, land surface and living organisms. There will be environmental, economic and social 'impacts' resulting from all these changes.

The MDB is one of Australia's largest drainage divisions, covering approximately one-seventh of the continent. It incorporates Australia's three longest rivers (the Murray, Darling and Murrumbidgee rivers) and contains more than 30000 wetlands, including 16 internationally significant wetlands that provide habitat for migratory birds. The MDB is also very important for rural communities and Australia's economy, with three million Australians inside and outside the Basin directly dependent on its water. About 85 per cent of all irrigation in Australia takes place in the MDB, which supports an agricultural industry worth more than $9 billion per annum.

The impact of climate change on the natural resources, industries and communities of the Basin is, arguably, the region's most pressing issue. In response to this, the Murray–Darling Basin Authority (MDBA) has recently funded a series of scientific reviews and syntheses, as well as more fundamental research, to begin to comprehend the effects and develop policy and management responses. The Authority has also taken climate change into account in its draft Basin Plan. This chapter broadly describes the observations of climate change in the MDB, future climate projections, recent advances in our understanding, incorporation of climate change in basin planning and future directions.

Human-induced climate change is a complex and contentious issue of global, regional and local significance. The risks and ramifications of climate change are large in terms of both impacts and measures to mitigate the causes. Consequently, the topic has been one of fierce debate, with science playing a central role in attempting to describe the causes, impacts and solutions. The far-reaching nature of the issue has meant that the science itself is frequently challenged.

This chapter attempts to summarise the current state of knowledge of climate change in the MDB and suggests future directions for research and investigation. In doing so, the chapter draws on the substantial body of international and national research and recent projects funded by the MDBA.

Definition of Climate Change

It is important for any chapter discussing climate change to be clear on definitions, scope and perspective. The Intergovernmental Panel on Climate Change (IPCC 2007:943) defines climate change as 'a change in the state of the climate that can be identified (for example, by using statistical tests) by changes in the mean and/or variability of its properties, and that persists for an extended period, typically decades or longer'. This definition is adopted here.

In terms of scope, climate change is taken to mean changes to the *climate system*—the highly complex interaction between the atmosphere, oceans, water cycle, ice, snow and frozen ground, land surface and living organisms. This is an important concept as it recognises the complexity, interactions, and chaotic nature of the system under study.

A simpler concept also used here is 'climate change and its impacts'. This conceptualisation essentially attempts to separate 'cause' and 'effect', with the change in climate variables (temperature, rainfall, and so on) causing impacts (bushfires, floods, and so on). This approach recognises 'feedbacks' from impacts to 'causes' that might amplify or reduce climate change.

The former *climate system* approach is an important scientific framework, whilst *climate change and impacts* can be a useful way of addressing the economic, policy and social issues.

The Science of Climate Change

The science of climate change has recently been well summarised by the Royal Society (2010 p13). Their general conclusion is:

> There is strong evidence that changes in greenhouse gas concentrations due to human activity are the dominant cause of the global warming that has taken place over the last half century. This warming trend is expected to continue as are changes in precipitation over the long term in many regions. Further and more rapid increases in sea level are likely which will have profound implications for coastal communities and ecosystems.

The Royal Society goes on to define the climate science that is agreed on, that has wide consensus but is still debated, and topics that are not well understood. The last aspects relevant to the MDB are:

- the net effect of changes in the carbon cycle in all current models is to increase warming—by an amount that varies considerably between models because of uncertainties in how to represent the relevant processes
- projections of climate change are sensitive to the details of the representation of clouds in models and the influence of particles on the properties of clouds; these are poorly understood
- the ability of the current generation of models to simulate some aspects of regional climate change is limited; there is little confidence in specific projections of future regional climate change, except at continental scales.
- the future strength of the uptake of carbon dioxide by land and oceans is very poorly understood
- observations are not yet good enough to quantify, with confidence, some aspects of the evolution of either climate forcing or climate change, or for helping to place tight bounds on climate sensitivity

In the MDB context, it could further be added that

- Global Climate Model (GCM) forecasts for precipitation are distributed almost equally between positive and negative change—hence, all that can be said reliably is that ‘it will be warmer and wetter OR warmer and drier’
- the regional climate modes such as the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Southern Annular Mode (SAM), Pacific Decadal Oscillation (PDO), Inter-Decadal Pacific Oscillation (IPO) and the Sub-Tropical Ridge (STR) are known to be important ‘drivers’ of MDB climate over a range of spatial and temporal scales; the interactions between these modes and with global climate change are not well understood.

Observations of Climate Change in the MDB

This section tabulates some observations of changes to the *climate system* in the MDB.

Table 4.1 Summary of observations of climate change in the MDB

Aspect of the climate system	Observed change
Annual mean temperature	A general upward trend in temperature is observed since the 1950s, with 2009 being the hottest year (Bureau of Meteorology: <www.bom.gov.au>; Figure 4.1). The decadal mean temperatures in the MDB (2000–09) show an increase of 0.53°C over the previous decade (1990–99). The spatial trend in mean annual temperature since 1950 shows the whole of the Basin increasing in temperature, with slightly higher rates towards the north-west. Warming has occurred in all seasons, however, the strongest warming has occurred in spring (about 0.9°C) and the weakest in summer (about 0.4°C) (CSIRO 2010).
Precipitation	The annual rainfall anomaly across the MDB shows no clear temporal trend at the Basin scale. 2010 saw the end to a long drought with the highest rainfall on record at 808 mm. When viewed spatially (Figure 4.2), however, there is a trend of increased drying in the south-eastern corner of the Basin. The spatial trend in heavy rain days for the Basin for the period 1970–2009 shows a declining trend across the MDB. Seasonal temporal rainfall trends for the MDB show little long-term temporal trends except for autumn, which shows a marked downward trend over the past two decades.
Pan evaporation	Annual pan evaporation temporal trends for the MDB show no clear trend; however, the spatial trends show broadly increasing pan evaporation in the southern Basin and decreasing in the northern Basin.
Stream flow	Precipitation in the MDB from 1997-2009 was significantly lower than the long-term average, and was accompanied by a 40 per cent reduction in stream flow in the southern MDB, where the majority of run-off is generated. During the period 2000–07, average annual inflow was 4150 GL/yr. In 2006–07, the 12-month stream flow reached a historical low of 770 GL/yr-1 to March 2007 (Cai and Cowan 2008; Figure 4.3). The average stream flow between 1998 and 2008 was 5700 GL—substantially lower than the long-term average of 11600 GL/yr between 1892 and 1997 (Kiem and Verdon-Kidd 2010). Despite these observations of unprecedented low stream flow in the Basin, the attribution of the reduction to climate change is highly complicated. Stream flow is heavily influenced by land-management practices, such as irrigated agriculture, forestry and water-management regimes determining the levels of diversions and water use from streams. Another confounding factor lies in the emerging understanding of the impact temperature change has on stream flow in the MDB. Determining plausible physical mechanisms underlying empirical temperature–stream flow relationships is subject to ongoing research (Yu et al. 2010). The record high rainfall of 2010 and resulting floods in 2010 and 2011 has re-directed attention to the potential effects of climate change on La Niña events (with added ocean warming), and cyclone, storm and rainfall intensities.

Aspect of the climate system	Observed change
Flooding/tropical cyclones	The flood seasonality for the north-east of the Basin shows predominantly summer/autumn flood events deriving from tropical troughs/lows (31 per cent) and remnants from tropical cyclones (12 per cent) (Grootemaat 2008). Trends in tropical cyclone activity in the Australian region (south of Equator; 105–160ºE) show that the total number of cyclones has decreased in recent decades; however, the number of stronger cyclones (minimum central pressure less than 970 hPa) has not declined.
Drought	The relative frequency of El Niño to La Niña events within a 15-year moving window during the past 600 years shows when more frequent El Niño events occur there are more likely to be periods of drought in Australia (Verdon-Kidd and Kiem 2010). This reconstruction indicates that more severe and prolonged periods of drought might have occurred in the Australian landscape in the past than what has been experienced since European settlement. Verdon-Kidd and Kiem (2009) conducted an analysis examining the climatic drivers and rainfall characteristics of the Federation (1895–1903), World War II (1935–45), and 'Big Dry' (1997–2009) droughts in Australia. These three droughts were found to vary in terms of their: primary climatic drivers (ENSO, IPO, IOD, SAM); severity (in terms of reduction of rainfall experienced from normal); spatial footprint; seasonality of rainfall reductions; and daily rainfall characteristics such as intensity and number of rain days.
Extreme temperatures and heatwaves	The annual maximum and minimum temperatures for the MDB over the period 1910–2009 show an upward trend and approximate increase of 1ºC (Bureau of Meteorology: <www.bom.gov.au>). The spatial trends in maximum and minimum daily temperatures (1970–2009) show strongly rising values across the MDB. The incidence of warm spells across the MDB has been increasing since 1910. The incidence of heatwaves (the number of worst annual three-day heatwave indices) is increasing across eastern Australia (Deo et al. 2006).
Bushfires	Since the 1950s, the climate has changed in ways that are likely to increase fire frequency and intensity in the MDB (CSIRO and BOM 2007): the average maximum temperature has warmed; south-eastern Australia has become drier; droughts have become hotter (Nichols 2004); and the number of extremely hot days (maximum temperature >40ºC) has risen. Although the relationship between climate and fire is confounded by factors such as arson and fire management, it is clear that hotter and drier years have greater fire risk.

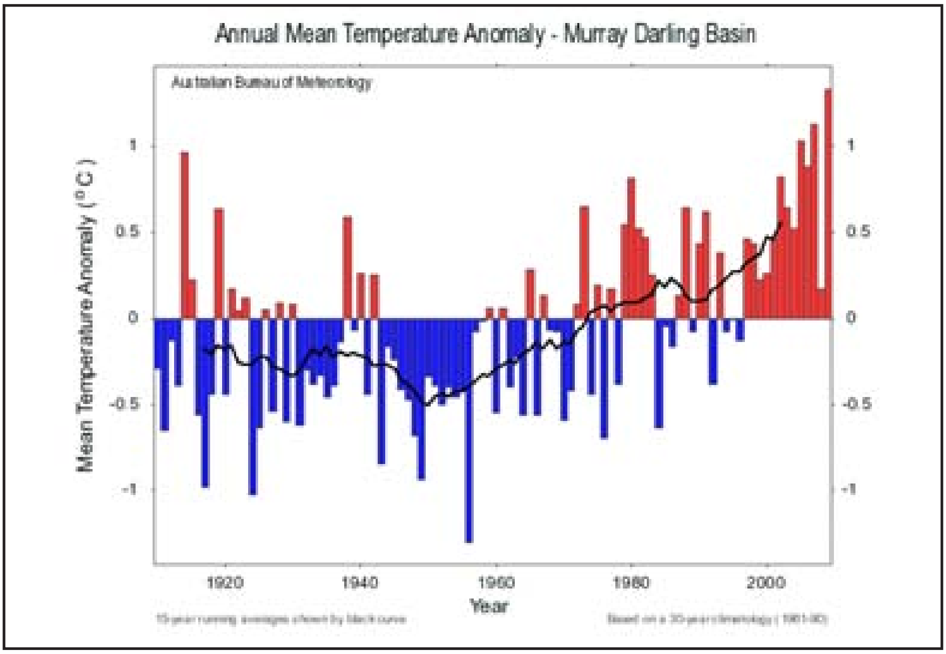

Figure 4.1 Annual mean temperature anomaly for the Murray–Darling Basin, 1910–2010, with 15-year running average (black line)

Source: Bureau of Meteorology: <http://www.bom.gov.au> accessed 20 March 2011

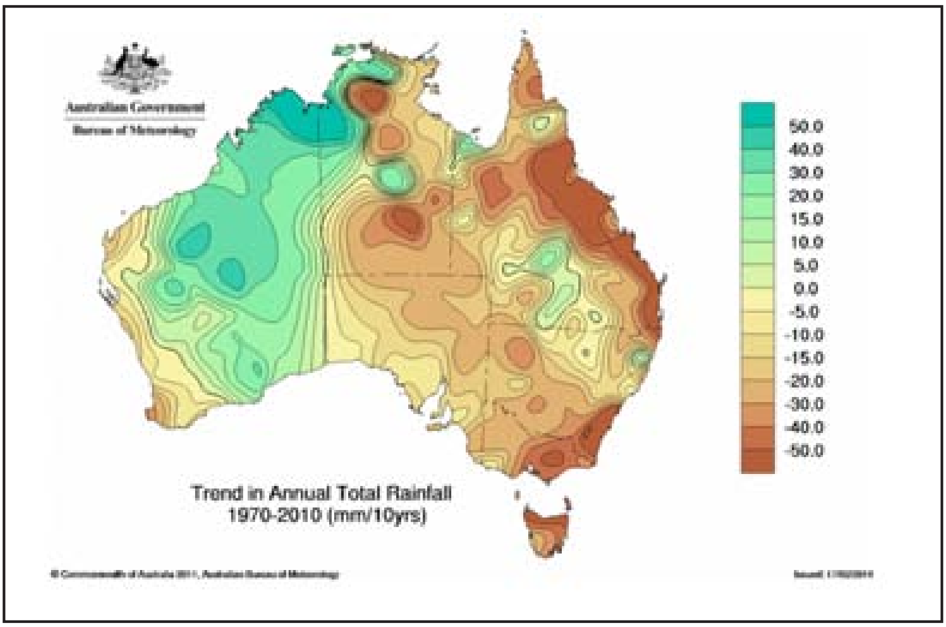

Figure 4.2 Annual rainfall spatial trend for the Murray–Darling Basin, 1970–2010

Source: Bureau of Meteorology: <http://www.bom.gov.au> accessed 20 March 2011

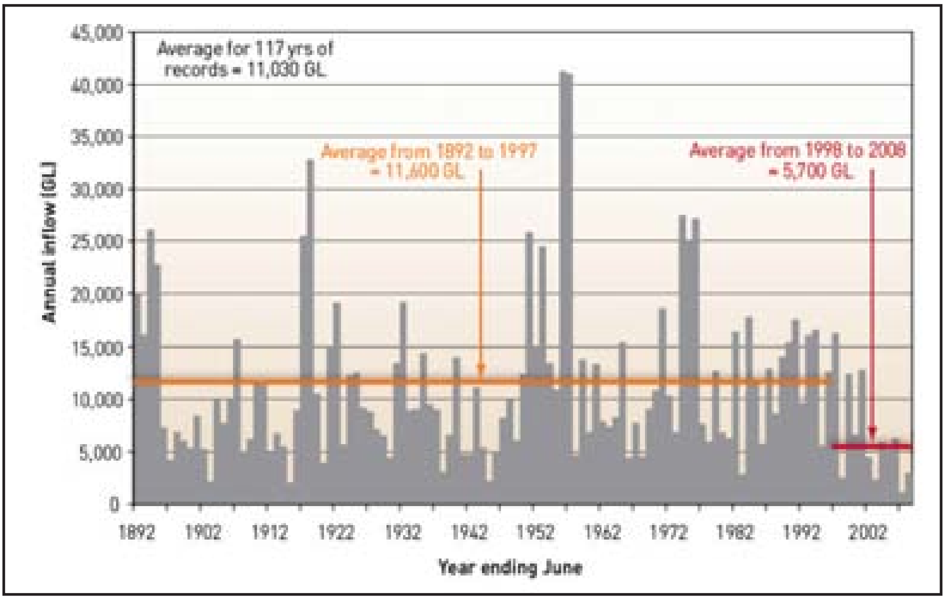

Figure 4.3 Record of annual inflows to the MDB 1892-2008

Source: Kiem and Verdon-Kidd (2010).

Future Climate Projections

Projections of future climate change in the MDB are summarised in Table 4.2.

Table 4.2 Summary of future climate-change projections in the MDB

Aspect of the climate system	Forecast changes in the MDB
Annual mean temperature	Increase in maximum surface temperatures across the MDB of 1–2°C by 2030 and up to 7°C by 2100; and increase in average surface temperatures across the MDB, particularly in the northern Basin, of 1–2°C by 2030 and up to 7°C by 2100. In winter, warming is projected to be as low as 0.5°C for the far south (CSIRO and BOM 2007).
Precipitation	The CSIRO's best estimate indicates that the future mean annual rainfall in the MDB in 2030 relative to 1990 will be lower by about 2 per cent in the north, and 5 per cent in the south (CSIRO 2008). Averaged across the Basin, the extreme estimates range from a 13 per cent decrease to an 8 per cent increase in mean annual rainfall (CSIRO 2008). In the southernmost MDB, the extremes range from a decrease in mean annual rainfall of up to 20 per cent to little change in mean annual rainfall (CSIRO 2008). In contrast to the CSIRO results, Sun et al. (in press) found almost zero change in MDB precipitation between 1970-99 to 2070-99, based on using an ensemble of 39 IPCC AR4 climate model runs for the A1B emissions scenario.

Evapotranspiration	Wet area evapotranspiration in the MDB has been projected for the years 2030 and 2100 based on a prediction from the CSIRO-Mk3.5, under SRES marker scenario A1F1, under a high rate of global warming. Predictions for 2030 show an increase in evapotranspiration in the range of 75–100 mm annually in the far north-east, 25–50 mm in the north-west, and 50–75 mm through the central and south-eastern parts of the Basin. By 2100, projections indicate a change of >175 mm annually for the entire Basin, with the exception of the far north-west, which is predicted to see increases between 125 mm and 150 mm annually (Figure 4.4).
Stream flow	The CSIRO Sustainable Yields project estimated changes in run-off in the MDB ranging from −33 per cent under a dry extreme scenario, and −9 per cent under a median scenario to a +16 per cent change under the wet extreme scenario (CSIRO 2008).
Flooding/tropical cyclones	It is likely that flooding in the northern part of the Basin will increase as monsoons are projected to be enhanced through climate change, and the northern Basin could become increasingly affected by tropical weather patterns (Grootemaat 2008). Abbs et al. (2006) indicate that tropical cyclone frequency could decrease by 9 per cent in 2070, but increases of 60 per cent (2030) and 100 per cent (2070) in the intensity of extreme tropical storms are possible.
Drought	Hennessy et al. (2008) project more frequent, longer, and more intense droughts in the MDB: • by 2010–40, exceptionally hot years are likely to affect about 65 per cent of the MDB and occur every 1.6 years on average • by 2010–40, little change is likely in the frequency and areal extent of exceptionally low rainfall years • by 2030, exceptionally low soil moisture years are likely to affect about 7 per cent of the MDB, and occur about once every 13 years on average.
Extreme temperatures and heatwaves	Global warming is projected to be associated with an increase in the frequency of hot days and warm nights. Daily maximum temperature data from six climate models were used to generate the ratio of the change in maximum to mean temperature. The ratio was more than 1 for the southernmost part of the MDB (CSIRO and BOM 2007).
Aspect of the climate system	**Forecast changes in the MDB**
Bushfires	Climate-change projections produced by the CSIRO show an overall increase in accumulated fire risk for Australia (CSIRO and BOM 2007). The combined frequencies of days with very high and extreme Forest Fire Danger Index (FFDI) ratings are likely to increase 4–25 per cent by 2020 and 15–70 per cent by 2050 (Lucas et al. 2007).

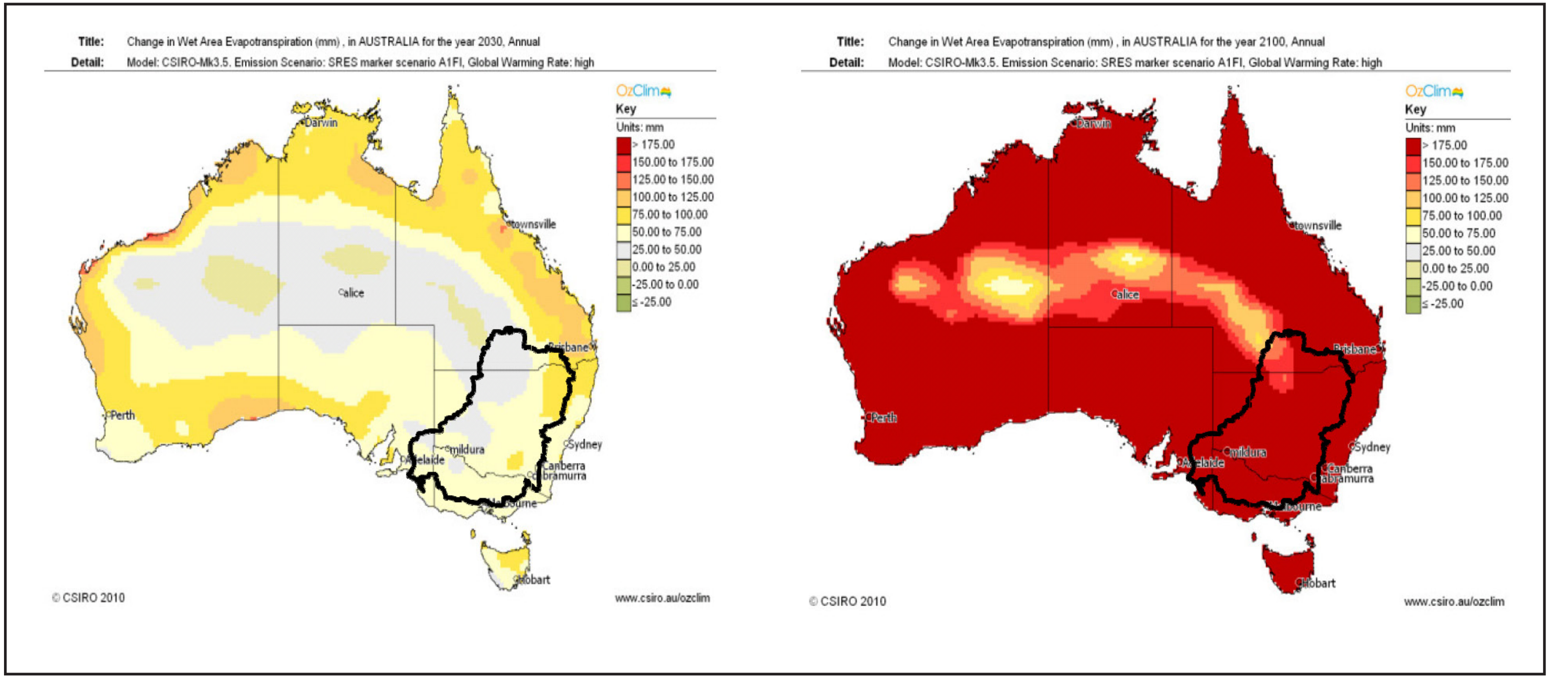

Figure 4.4 Wet area evapotranspiration (mm) in the MDB, 2030 and 2100

Note: Based on a prediction of the CSIRO-Mk3.5, under SRES marker scenario A1F1, under a high rate of global warming.

Source: CSIRO (2010).

Recent Advances in Understanding

Recent syntheses and investigations funded by the MDBA are summarised in Table 4.3. This work is as yet unpublished and summaries are presented with author and MDBA permission.

Table 4.3 Recent synthesis studies funded by the MDBA

Author(s)	Project title	Summary
CSIRO/BOM	South East Australia Climate Initiative	Links between the observed autumn rainfall decline in the MDB and a strengthening of the subtropical ridge (STR) have been made.
Anthony Kiem and Danielle Verdon-Kidd	Review of current understanding of Murray–Darling Basin climate patterns and causal processes	Dry conditions in autumn across the southern MDB are most likely if an El Niño event occurs in combination with a positive SAM. It was also found that, unlike the majority of eastern Australia, in the southern MDB, a La Niña event is not necessarily always associated with above-average rainfall. In fact, La Niña events occurring in conjunction with a positive SAM phase are often as dry as an El Niño event for the southern MDB.
Ailie Gallant and David Karoly	Climate patterns and causal processes	The MDB is broadly discussed in two regions: the north, where tropical influences dominate, and the south, where mid-latitude processes are most important. The ENSO is the most important driver of inter-annual variability across the MDB. Indian Ocean sea-surface temperatures (SSTs), including the IOD and the SAM, are regionally important during some seasons. The PDO is an important regulator of decadal climate variations in the MDB.
Roger Stone	Comprehensive review into the core patterns, droughts, rainfall systems and associated causal processes relevant to the Murray–Darling Basin at a range of associated time scales	ENSO has been and remains a major driver of year-to-year rainfall variability over the MDB, with strong impacts during the winter, spring and summer. Impacts in summer are especially relevant for northern regions of the MDB through affecting inflow into the MDB system via northern river systems influenced by tropical and extra-tropical systems. Additionally, the IOD, especially when considered in conjunction with ENSO, can influence rainfall variability over the MDB.
Jason P. Evans, Andy J. Pitman and Faye T. Cruz	Scientific review of the atmospheric and land-surface dynamics of the Murray–Darling Basin	While the climate of the MDB is dominated by large-scale processes, the nature of the landscape, the vegetation, soil moisture, fire, irrigation and orography interact with the large-scale forcing. Some of these terrestrial processes are locally important but regionally are likely to be insignificant. Others, through spatial aggregation of the small-scale processes, might lead to amplification or moderation of the larger-scale forcing.

Michael Roderick & GrahamFarquhar	Water availability and evapotranspiration in the Murray–Darling Basin: a look at the past and a glimpse into the future	The Budyko framework is used to calculate catchment-scale evaporation and run-off as a function of two climatic factors—precipitation (P) and evaporative demand (E)—and a third parameter (n) that encodes the catchment properties. The effect of GCM-projected changes in P and E on run-off is estimated (other factors remaining constant).
Peter Gell and collaborators	Palaeo-climate studies relevant to natural-resource management in the Murray–Darling Basin	Studies relating to past climate change and variability across south-eastern Australia have used speleothems, tree rings, river channels and terraces, dune systems and lake sediments. Available scientific evidence reveals that the Murray–Darling Basin has, over the past few hundred years, been subjected to extended inter-decadal variability, known as flood and drought-dominated phases, and year-to-year ENSO variability.
Peter Helman	Droughts in the Murray–Darling Basin since European settlement	In general, MDB droughts occur during positive IPO phases, with severe drought years linked to negative SOI or IOD. These climatic indices, while providing indicative correlations, do not correlate with all events. The drought history of the Basin shows that for more than one-third of the 221 years since European settlement part or all of the Basin has been in drought. Two long drought periods from 1795 to 1830, extending over 35 years, and 1980–2009, extending over 29 years, show a complete alteration to the water cycle.
Tim Low	Climate Change, Weeds and Pests in the Murray–Darling Basin	The evidence suggests that most of the weeds assessed are likely to benefit overall from climate change. Reasons for this include longer growing seasons, less frost, more droughts reducing competition, and higher temperatures along with carbon dioxide fertilisation increasing plant growth rates in situations where water is not limiting and competition from native plants is minimal. Climate change should lower populations of exotic fish because there will be less habitat for them to occupy.
Wendy Proctor, Karin Hosking, Thomas Carpenter, Mark Howden, Mark Stafford Smith and Trevor Booth	Future research needs for climate-change adaptation in the Murray–Darling Basin	Knowledge about adaptation is quite limited. There is a need for adaptation thinking to embrace the need for transformative, rather than incremental, adaptation in the region, which requires a major program to help the policy and management communities to envision different futures. It is likely that institutional change will be required as part of the process of responding to this challenge.
Bonnie Bonneville, Julie Morris, Emma Collins, David Dettrick and Annie Sanderson	Impacts of Climate Change on the Murray–Darling Basin's Water Quality	Impacts of climate-related extreme events (prolonged droughts, bushfires, heatwaves, flooding, and dust storms) on water-quality parameters (dissolved oxygen, nutrients, turbidity, salinity, water temperature, pH and BOD) were assessed across the MDB. Resulting risks to beneficial uses were rated for each event type for different regions of the Basin.

Fran Sheldon, Nick Bond, Nick Marsh, Stephen Balcombe, Samantha Capon, Wade Hadwen and Mark Kennard	Impacts of Climate on the Aquatic Ecosystems of the Murray–Darling Basin	Three climate-change drivers for inland aquatic ecosystems were reviewed: increasing temperature (air and water), changing patterns of precipitation (rainfall and run-off), and increased UVB-radiation. Impacts were reviewed for a range of fish, riparian and floodplain vegetation species.
Quentin Grafton, Angella Duvnjak, Chris Miller, Paul Ryan, Fiona Verity, Mavis Zutshi, Jared Dent, Qiang Jiang, Michael Ward, & William Nikolakis	Potential Water Quantity and Quality Impacts in the Murray–Darling Basin from Communities and Industries Responding to Climate Change	Impacts of wet and dry future climate scenarios on irrigated agriculture, aspects of dryland agriculture, aspects of forestry and tourism, basin communities, and Indigenous peoples were assessed though modelling and community workshops.
Greg Holland, Keith Collett, Nicole Caruso and Bonnie Bonneville	Risk of climate-change impacts on salinity dynamics and mobilisation processes in the Murray–Darling Basin	A quantitative and qualitative assessment of the impact of wet and dry climate scenarios to 2050 on salinity loads and concentrations is made for broad regional landscapes as well as the Darling tributaries and Murray River. A risk assessment is conducted and some options for management presented.
Tim McVicar, Randall Donohue, Anthony O'Grady and Lingtao Li	The effects of climate change on plant physiological and catchment eco-hydrological processes in the high-rainfall catchments of the Murray–Darling Basin: a scoping study	This project explores the sensitivity of run-off in the context of climate change across the MDB to changes in five key eco-hydrological parameters: annual precipitation, annual potential evaporation, average storm depth, catchment-average rooting depth, and atmospheric carbon dioxide concentration. The sensitivities were analysed for five MDB water-resource yield zones: the extremely high yield zone (EHYZ), the very high yield zone (VHYZ), the southern high yield zone (sHYZ), the northern high yield zone (nHYZ), and the whole Murray–Darling Basin.
Peter Gehrke	Afforestation risks to water resources in the Murray–Darling Basin	The risks to MDB water resources of afforestation under climate change were assessed. Catchment water yields were analysed for climate change alone and climate change with afforestation. Recent work on the adaptive capacity of forests to climate change and effects of industry plantation projections were also taken into account.
Leon Bren, Jeya Jeyasingham, Stuart Davey, Patrick Lane, Richard Benyon and Ian Ferguson	Impacts of native forest management practices in silvicultural systems on catchment water yield in the MDB	The past 13 years in Victoria were viewed as similar to the more extreme levels of reduced rainfall estimated to potentially occur due to future climate change. Using this, estimates were made of the reduction in rainfall that might be expected and the impact of this on stream flow should logging cease in the higher-rainfall, forested catchments of the MBD.

Basin Planning and Climate Change

The *Guide to the proposed Basin Plan* (MDBA 2010a) was prepared on the basis of modelling that shows surface-water availability declining by 10 per cent between 1990 and 2030. The story for groundwater is somewhat different, with the MDBA's modelling for the same period suggesting that groundwater recharge will remain at about historical levels. The Authority also noted that while 'there is an increasing likelihood that climate change is part of the reason for the recent drought, it is not yet possible to distinguish this component from the naturally high climatic variability experienced in the Basin'.

The MDBA's modelling is based on the entire historical record (1895–2009), which incorporates data from the first half of the period 1990–2030. As a consequence, the 10 per cent reduction due to climate change is already partially accounted for in existing hydrological modelling used for basin planning. With the Basin Plan set for review by 2021, the Authority considered it 'only appropriate to incorporate a percentage of the remaining change not already in the modelling' in the Basin Plan. The Authority determined that a 3 per cent reduction in surface-water availability was appropriate and factored this reduction into calculations for the sustainable diversion limits (SDLs). The implication here is that the 3 per cent reduction will be revisited when the Basin Plan is reviewed in 2021. The arrival of the MDBA at a 3 per cent reduction in the availability of surface water is not made clear in the Guide, but is understood to be a proportional estimate. This 3 per cent is applied across the Basin without attempting to take into account local variations. It should be noted that as water-resource plans will allocate water on an annual basis, reductions in water availability due to climate change will be accounted for and shared between the environment and other users.

The MDBA has relied upon the Sustainable Yields methodology and models for determining the impacts of climate change on rainfall, run-off and other climate-driven variables (MDBA 2010b). Volume 2 of the Guide quotes the CSIRO Sustainable Yields project, which found there would be an 11 per cent reduction in surface-water availability in 2030 under the median climate scenario (MDBA 2010b). This methodology uses high, medium and low global greenhouse gas emission scenarios based on the IPCC's *Fourth Assessment Report* and the work of CSIRO and the Bureau of Meteorology (BOM). The changes in temperature under these scenarios are multiplied by the estimated changes in rainfall and other variables per degree of warming that have been calculated from 15 global climate models from the *Fourth Assessment Report*. The results are 45 sets of 'seasonal scaling' factors that are applied to the historical record to arrive at a range of predicted outcomes of climate change, including changes to rainfall and run-off (Chiew et al. 2008).

The MDBA (2010b) considers itself to have factored climate change into the Basin Plan in three ways

1. the 3 per cent reduction in surface-water availability by 2021
2. requiring flexibility in water-resource plans to operate across a range of climatic conditions
3. the sharing of climate-change effects evenly between the environment and water users.

Work on the final Basin Plan is ongoing and revisions are expected in the way that climate-change impacts are determined in the final Basin Plan (due in 2012).

Concluding Remarks and Future Directions

The constraints of word length and unpublished material mean that justice has not been done to this topic and the growing body of knowledge it encompasses. It is clear, however, that climate change is now an integral part of the environmental, economic and social futures of the MDB. This chapter at best gives an introduction to this complex sphere and some of the emerging ideas and analyses. A more comprehensive synthesis is under way.

In this final section, some broad priorities for future investigation are proposed. Many more specific needs have been identified but are too numerous to report here.

Perhaps the overriding constraint in describing and assessing future climate change and its impacts is the ability of GCMs to provide accurate climate forecasts at the scale of the MDB. This issue has been highlighted by the Royal Society (2010), which states that 'there is little confidence in specific projections of future regional climate change'. GCMs also do not adequately take into account regional modes of climate variability (prominent in the Australian context), land surface–atmosphere coupling and some feedback processes in the carbon cycle. This further limits their capacity to provide realistic forecasts at the MDB scale. This issue of forecast quality is critical to assessment of future impacts of climate change in the MDB as climate inputs drive most impact assessments.

To address this quandary, modellers have developed future climate scenarios that capture both a range of future greenhouse gas emission scenarios and a range of forecasts by the different GCMs. Such scenarios are useful for asking 'what if' questions, and perhaps in putting some reasonable bounds on future possibilities.

Despite the scenario approach, it is proposed that uncertainty in climate-change forecasting needs to be addressed more explicitly and communicated more effectively. There are many sources of uncertainty in models to be considered, including the: key processes selected and omitted; different representations/codifications of processes; selection of model parameter values; representation of interactions between processes; inclusion of important feedback mechanisms; treatment of processes not fully understood; effects of different model structures; impacts of using different antecedent conditions; error cascades in down-scaling; selection of future emission scenarios. These and other factors can create a wide range in the uncertainty of forecasts. Current methods to account for uncertainty in climate projections are also limited—for example, the use of statistics applied to ensembles of projections based on intrinsically different models, or assumptions relating to commonality in forecasts from different models equating to accuracy of forecasts. Hence, greater effort to characterise and communicate uncertainty is proposed.

Most users of climate information seek forecasts at a particular spatial scale of relevance. This scale is often small in relation to the forecast capability of GCMs. Down-scaling techniques have been used to assist in translating GCM forecasts to local scales, but it should be noted that these techniques do not improve the quality of the GCM forecasts used.

The natural variability of the Australian climate—and that of the MDB—is amongst the highest in the world. This is due in part to a number of regional-scale climate 'modes' that affect the climate over weeks, months, seasons, years and decades. The modes include: ENSO, IOD, SAM, IPO/PDO and STR, amongst others. Each of these modes affects climate outcomes over different spatial and temporal scales and some interact with each other. There are also some indications that global warming is influencing some of these modes. Research on these aspects of climate variability and interactions with climate change is progressing, but much more effort is required in this domain.

Landscape type, vegetation, soil moisture, fire, irrigation and orography interact with the large-scale climate forcing in complex ways. Whilst these are primarily second-order effects, more research is required on the role of each aspect in climate outcomes.

Warming has been occurring in the MDB since the 1950s (Figure 4.1) and numerous climate trends are evident in climate observations. It is proposed here that more emphasis should be placed on observations of climate change in the instrumental and palaeo-climate records as a means of understanding and assessing impacts of past and future climate change, particularly given the limitations of future GCM forecasts and their inability to account for some current observed trends such as autumn rainfall decline.

The scientific evidence for global warming and ongoing changes in the climate system is very strong, and the potential short, medium and long-term consequences range from substantial to catastrophic. Climate change and climate variability are arguably the most important drivers of future change to the natural resources of the MDB and might have significant impacts on industries and communities. Clear, well-argued priorities for research to meet the adaptation needs of all sectors of the community should be agreed to and financially supported.

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