Review of Water Reform in the Murray-Darling Basin
Appendix 4. Climate change in the Murray-Darling Basin

Climate change in the Murray-Darling Basin: an update

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Summary

This report provides an up-to-date assessment of how climate change is affecting the Murray-Darling Basin using published information. Two key elements of this task are to review implications for the Basin of CSIRO's latest climate change projections, and to assess the continuing relevance of the detailed hydrological climate change projections for the Basin provided by Murray-Darling Basin Sustainable Yields project in 2008.

The Basin area has warmed by around a degree since 1910, and will continue to warm (by 0.6–1.5 ^{o}C in 2030 relative to 1995, and by 0.9–2.5 ^{o}C in 2050 without mitigation), with more hot days and fewer cold days. Rainfall is projected to have a tendency to decrease, particularly in the south and in winter, with more time in drought and decreased soil moisture. However, both natural variability and model-to-model differences are large, and both increased and decreased rainfall are possible, particularly in the north. Daily extreme rainfall is projected to increase even if average rainfall declines, with implications for erosion and flooding among other impacts.

Using a climate analogue approach, sites in the Basin 'move' inland/northwest under the hottest/driest scenario and north/northeast in the coolest/wettest scenario. The analogues may be many hundreds of kilometres away and outside the Basin in 2050 under high emissions, representing a substantially different climate.

Wet and dry extreme climate scenarios used in Sustainable Yields (CSIRO 2008b) were assessed as still valid and representative given latest science, and thus the consequent hydrological scenarios are similarly still valid and representative (although latest modelling results suggest that the probability of the dry scenario may have declined slightly). For the dry scenario there are large reductions runoff and water availability throughout the Basin. For the wet scenario there are significant increases in runoff and water availability in the north grading to little change in the south.

Introduction

The purpose of this report is to provide an up-to-date assessment of how climate change is affecting the Murray-Darling Basin. The report has been commissioned by the Wentworth Group as a contribution to an independent review that it is undertaking of progress on implementation of the Murray-Darling Basin Plan.

The particular focus of this report is on the question of how climate change has affected, and is anticipated to affect, water availability in the Basin. Subsequent questions of how climate change could affect the ability to deliver Basin Plan objectives; and long-term policy implications and recommendations for managing and adapting to climate change impacts in the Murray-Darling Basin will be addressed in a subsequent report. This report will also provide detailed climate and hydrological scenarios to assist in addressing these questions.

This report is a desk top study which reviews information on climate change relevant to impacts in the Basin, based on the latest science and drawing from a range of assessments currently available. There are three major sources of information: the Murray-Darling Basin Sustainable Yields (SY) project representing the most comprehensive assessment of the impact of climate change on hydrology in the Basin (CSIRO 2008b), CSIRO's latest climate change projections released in 2015 (Climate Change in Australia – CCIA) (CSIRO; BoM 2015), and the historical climate information from the Bureau of Meteorology. Reference is also made to the regional projections of the Victorian Climate Initiative (VicCI) (Timbal et al. 2016) and the NSW/ACT Regional Climate Modelling (NARCLiM) project (Evans et al. 2014), and to the results of the South Eastern Climate Initiative (SEACI) (CSIRO 2012).

As new hydrological modelling is beyond the scope of this report, the wet and dry scenarios for water availability 2030 as documented in CSIRO's Murray-Darling Basin Sustainable Yields Project are re-presented here. Any necessary adjustments to the conditions under which they may occur given the latest climate modelling are assessed and also presented.

This report begins with an assessment of recent observed climate variability and change in the region and its causes. The latest sources of information, such as new climate modelling results, are introduced and described. Then projected future climate change for the region in 2030 and 2050 is presented based on relevant material drawn from the CCIA projections. This includes changes to means and extremes of temperature, rainfall and a range of climate variables relevant to Basin management. To further illustrate the changes in climate, sites with current climates analogous to the future climates of some key sites in the Basin are identified. Next, to provide context for the hydrological scenarios a comparison is made between current climate modelling results and those available when the SY hydrological results were produced. Finally, the Wet and Dry hydrological scenarios for 2030 from SY are presented along with a current assessment of the conditions under which they may occur. The Wet and Dry scenarios from SY are given greater emphasis here rather than Median scenario (which represents little rainfall change), as this correctly emphasises that substantial rainfall change is very plausible (even if the direction of change is uncertain) and that this needs to be considered from a risk management perspective.

Geographical regions used in this report

Here the Murray-Darling Basin region, as illustrated in Figure 1, is used for basin-wide statistics, such as area-averaged historical climate trends from the Bureau of Meteorology.

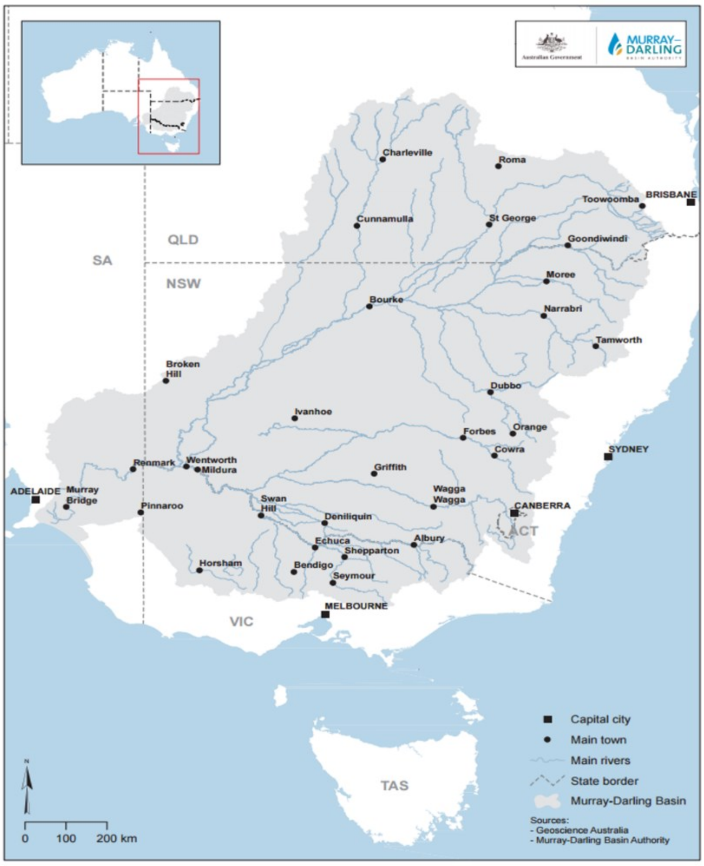

Figure 1: Murray-Darling Basin (Source: http://www.mdba.gov.au/publications/maps-spatial-data)

Climate change projections in this report are based on the regionalisation of Australia used in CCIA (CSIRO; BoM 2015). This divided Australia into eight regions (known as 'clusters') based on a clustering of natural resource management regions (see Figure 2). The Basin is predominantly comprised of two of these clusters: 'Murray Basin', representing the Murray catchment, and 'Central Slopes', representing the upper Darling catchment (Figure 3). The northwest portion of the MDB also falls partially into the Rangelands cluster, but this report will focus on the climate change results for the Central Slopes and Murray Basin clusters as the hydrologically important clusters for the Basin.

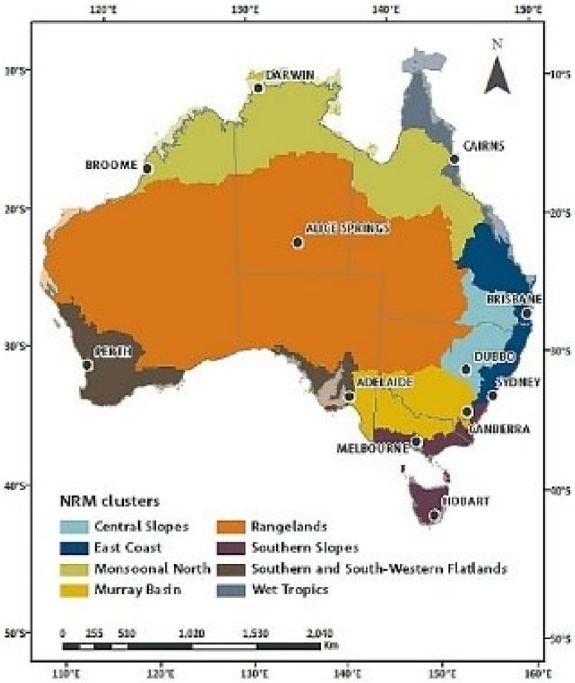

Figure 2: Regions used in the CCIA climate projections. Source: reproduced from (CSIRO; BoM 2015).

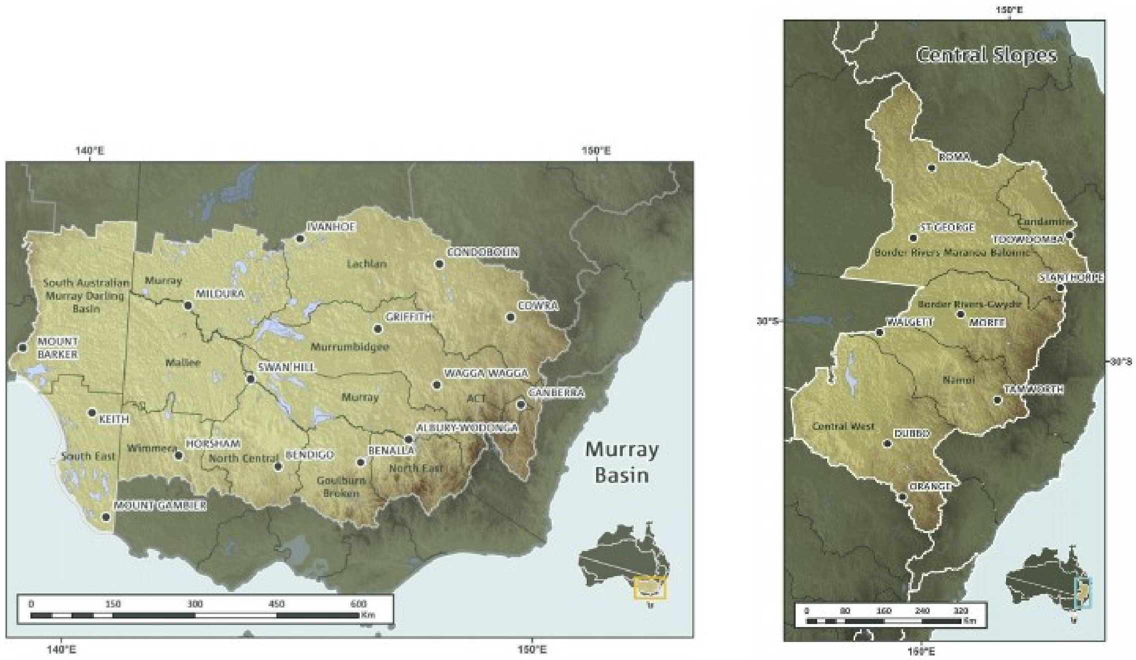

Figure 3: Murray Basin and Central Slopes clusters from CCIA. Source: reproduced from Ekström et al (2015) and Timbal et al (2015).

Historical climate change

Temperature has increased historically across the Basin since the beginning of good quality records in 1910 (Figure 4, top left). This has been more marked since 1950 and the four warmest years since 1910 have occurred in the last ten years. Warm season temperature (Figure 4, top right) shows the seasons of 2009/10 and 2010/11 as slightly anomalously cool as a consequence of wet conditions (see below), although with a return to drier conditions in recent years, temperatures have returned to those typical of the last decade. The warming since 1910 has occurred in the all parts of the Basin (Figure 4, bottom left) and in both maximum and minimum temperatures as well as mean temperatures. Calculated from the data for the Basin area downloadable from the BoM website (http://www.bom.gov.au/climate/), Basin-wide average increase in mean temperature over 1910-2015 based on BoM data is +0.9 ^{o}C, and that for maximum temperature is +0.7 ^{o}C and that for minimum temperature is +1.2 ^{o}C. There has also been a marked increasing trend in the frequency of hot years and a decreasing trend in cold years (Figure 5). Attribution of Australian region warming at least in part to anthropogenic climate change was established by Karoly and Braganza (2005).

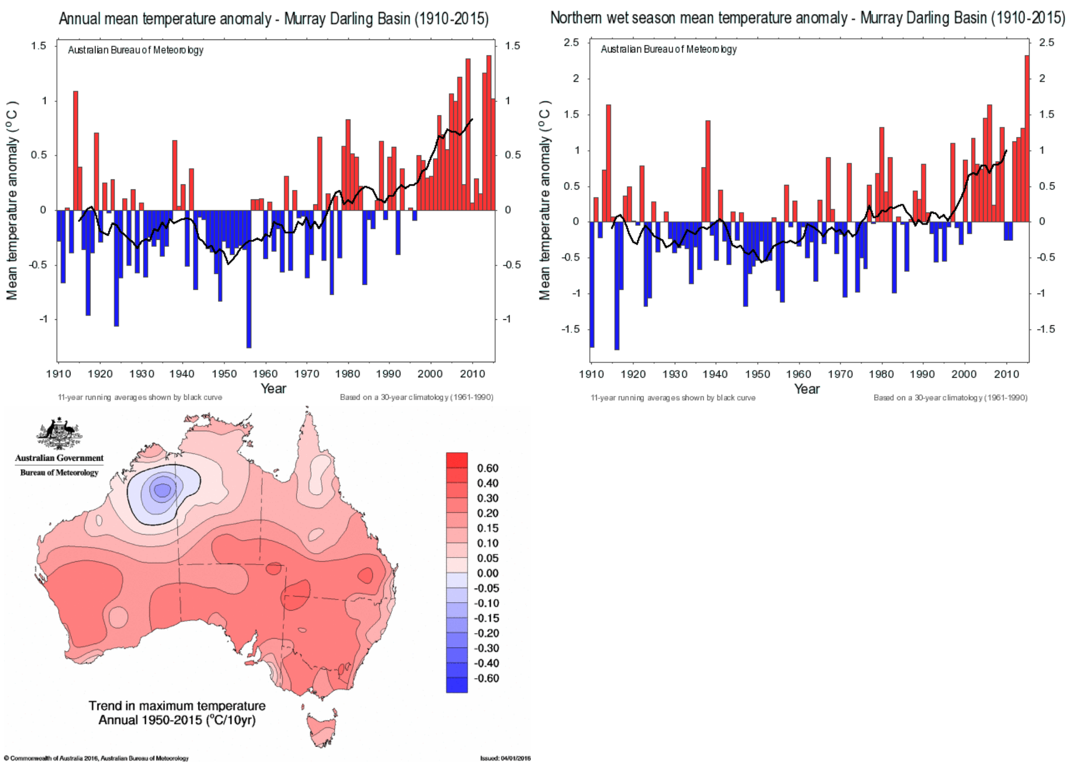

Figure 4: Mean temperature anomaly (with 11-year running mean in black) averaged across the MDB annually (top left), for October to April (top right), and the spatial distribution of the rate of temperature change for 1950 – 2015 (bottom left). Source: BoM website (http://www.bom.gov.au/climate/).

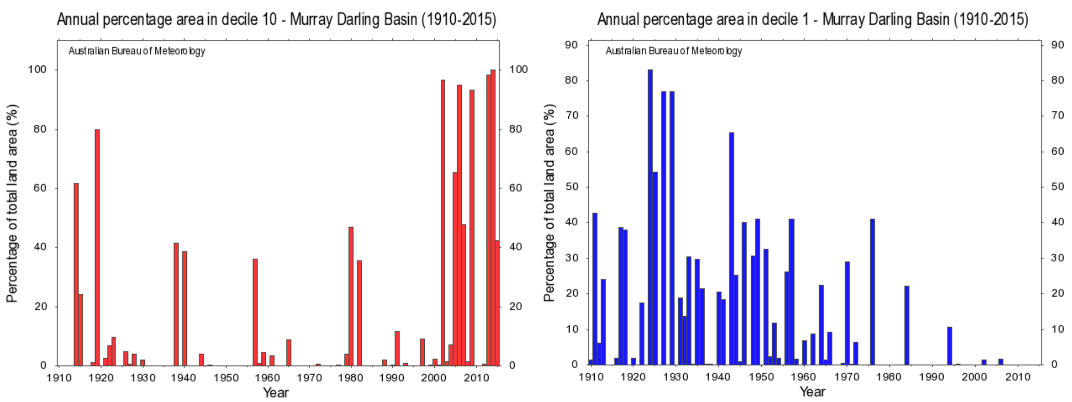

Figure 5: Variation in the area of the Basin experiencing unusually warm conditions (annual average maximum temperature anomaly of Decile 10) (left) and unusually cold conditions (annual average minimum temperature anomaly Decile 1) (right). Source BoM website (http://www.bom.gov.au/climate/).

Precipitation does not show clear trends in the same way that temperature does. Annual rainfall averaged across the Basin for 1900-2015 is shown in Figure 6 (top left). As well as the high natural variability, the Millennium drought (Leblanc et al. 2011) is particularly evident over 2001-2009, followed by the very wet 2010-2012, and finally a return to dry conditions in the subsequent years up to present. Earlier drought periods are evident, such as in the 1940s and 1930s. If the rainfall is broken down according to cool and warm seasons for the Basin (using BoM's southern and northern wet seasons, see Figure 6 caption for definition), there is a marked tendency for the Basin to have become drier in the hydrological and agriculturally important April to October period (Figure 6, compare bottom left with top right). All cool seasons have been dry since 2001 except 2005 and 2010. Drying is less marked in the warm season, for which there has been more frequent and larger positive anomalies, most notably the summers of 2009/10 and 2010/11. This cool season/warm season dichotomy in rainfall behaviour is most evident in the southern half of the Basin where the winter drying has been even stronger. In fact, for Victoria, the dominance of cool season rainfall over warm season rainfall has weakened in the past decade to its lowest recorded level (Timbal et al. 2016).

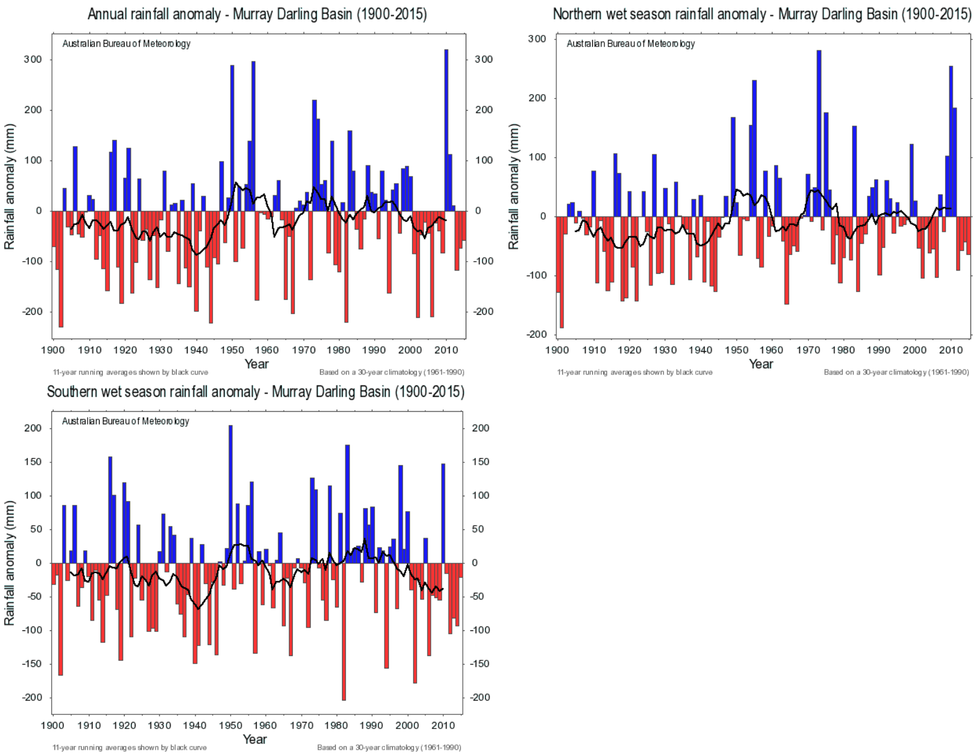

Figure 6: Precipitation anomaly averaged across the MDB annually (a), for the northern wet season, October to April (b), and the southern wet season, April to October (c). 11-year running mean indicated in black. Source: BoM website (http://www.bom.gov.au/climate/).

The Millennium Drought was of great hydrological importance to the MDB, particularly the southern MDB (Leblanc et al. 2011). Potter et al (2010) note that the reductions in runoff were unprecedented in the historical record and estimated their return period as 1/300 years. Notably the runoff was more reduced than may have been expected given the rainfall anomaly, a tendency that has been attributed (in a study for a catchment in the Southern Basin) to increases in potential evapotranspiration and changes to rainfall variability and seasonality (Potter; Chiew 2011). MDB rainfall (Ho et al. 2015) and Murray streamflow (Gallant; Gergis 2011) records have been extended back into the pre-instrumental period using various palaeoclimatic indicators. These studies suggest that larger and more extended dry spells may have occurred in the more distant past, although Gallant and Gergis (2011) estimate the return period of the Millennium Drought as having a 1/1500 years based on past climatic variability.

The dry conditions in the cool season over southeastern Australia since 1996, and affecting the southern MDB, are associated with a southward expansion of the atmospheric Hadley cell and a southward shift of the storm track (CSIRO 2012; Post et al. 2014). The change in rainfall and circulation agree qualitatively with that simulated under enhanced greenhouse conditions and have been partially attributed to anthropogenic influence, along with natural variability (CSIRO 2012; Timbal et al. 2016). The unusually wet conditions of December 2010 may also have been influenced by anthropogenic climate conditions, as the La Nina- related high rainfall appears to have been enhanced by unusually high regional sea surface temperatures (Evans; Boyer-Souchet 2012).

Basis for Projections

The quantitative projections to be presented here are drawn from the CCIA projections (CSIRO; BoM 2015). The basis of these projections are the results of the CMIP5 ensemble of climate models run under scenarios of increasing levels of greenhouse gases and atmospheric aerosols, known as the Representative Concentration Pathways (RCPs). The CMIP5 ensemble represents the latest round of climate model simulations from the major modelling centres around the world, and are also the simulations used by the IPCC (Taylor et al. 2012). The RCPs comprise: RCP8.5 (high emissions and thus greatest impact on the climate), RCP4.5 and RCP6.0 (intermediate emissions and climate impact) and RCP2.6 (low emissions and least climate impact) (Van Vuuren et al. 2011). The RCP8.5 future involves little reduction to current emission patterns, whereas at the other extreme, RCP2.6 represents a very ambitious program where emissions peak by 2020 and decline rapidly after that to eventually less than zero. See further discussion in CSIRO & BoM (2015). Results presented here are primarily for RCP4.5 and RCP8.5.

Projections for future climate change are conditional on a particular RCP, although results differ little according to RCP in the near term (2030). The effect of RCP differences is a little more important by 2050 (and very important later in the century).

Even for a given RCP, projections need to be presented as ranges. This is because there is a range of regional responses to enhanced greenhouse conditions that currently can be seen as plausible, and the spread of results between different climate models can be used as an estimate of this range. Natural variability of climate (present in models and in the real world, but with different phasing) also contributes to the ranges produced, particularly in the near term when signals may be weak compared to natural variability. Selecting some models over others based on their ability to simulate aspects of current regional climate can provide increased apparent certainty (e.g., Smith and Chandler (2010) using earlier generation GCMs), but after an extensive review CCIA concluded that this approach was not sufficiently justified for the Australian results of the CMIP5 ensemble and CCIA used all available CMIP5 models to form ranges of change (see further discussion in CSIRO & BoM (2015)). That conclusion is accepted here.

Projections for the basin

Temperature

Projected mean temperature change for 2030 and 2050 relative to 1995 for the southern and northeast regions are given in Table 1, based on the analysis of CCIA (CSIRO; BoM 2015). Projected warming in 2030 relative to 1995 is around 0.6 – 1.5 ^{o}C, with the main source of variation being model differences (variations in the emission scenario have little effect). Projected warming is slightly stronger in the north, than in the south. By 2050 sensitivity to assumed emissions is more noticeable with projected warming of 0.9 - 1.9 ^{o}C for RCP4.5 and 1.3 -2.5 ^{o}C for RCP8.5 and with warming a little higher in the north than in the south. It is notable that the increase to date in mean temperature, relative to 1995, is already around 0.5 ^{o}C (see Figure 4), suggesting that the lower bound of 0.6 ^{o}C for the projected warming is very likely to be exceeded.

These warmings are large compared to natural variability (see Figure 7 for an example of projected warming as a time series using the results from a single climate model under RCP8.5). Warming for maximum and minimum temperature are similar to that for mean temperature (CSIRO; BoM 2015).

Table 1: Average warming in °C for the Murray Basin and Central Slopes in 2030 and 2050 and under RCP2.6, RCP4.5 and RCP8.5. Baseline is 1995 (1986-2005). Source: Climate Change in Australia website.

		RCP2.6	RCP4.5	RCP8.5
2030 (2020-2039)	Murray Basin	0.8 (0.6-1.0)	0.8 (0.6-1.1)	0.9 (0.7-1.3)
	Central Slopes	0.9 (0.6-1.2)	1.0 (0.6-1.3)	1.1 (0.7-1.5)
2050 (2040-2059)	Murray Basin	1.0 (0.6-1.3)	1.3 (0.9-1.7)	1.7 (1.3-2.1)
	Central Slopes	1.0 (0.7-1.6)	1.4 (1.0-1.9)	1.9 (1.3-2.5)

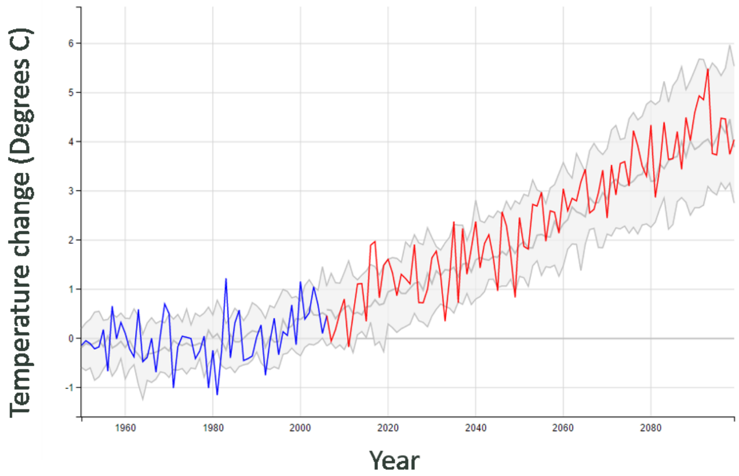

Figure 7: Example of model simulated historical (blue) and projected (red) annual temperature (in C) for Murray Basin region from a single global climate model (ACCESS-3 model, RCP8.5). Grey envelope indicates results from multiple models. Source: Time Series Explorer, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/climate-projections/explore-data/time-series-explorer/)

These projected warmings are expected to apply to daily temperature extremes, increasing the temperature of hot days and cold nights, and increasing the frequency of hot nights but reducing the frequency of cold nights. CCIA concluded for Murray Basin based on model results and physical understanding: "A substantial increase in the temperature reached on the hottest days, the frequency of hot days and the duration of warm spells are projected with very high confidence" (Timbal et al. 2015). Similarly they concluded: "a decrease in the frequency of frost days is projected with high confidence" (Timbal et al. 2015). CCIA conclusions for the northeast of the Basin (Central Slopes) were similar (Ekstrom et al. 2015). Table 2 gives an example of projected changes in the frequency of days over 40 °C and frosty nights for a site in the Basin (Bendigo).

Table 2: Projected mean frequency of days at Bendigo with maximum temperature over 40 °C and days with minimum temperature under 2 °C. Source: Threshold Explorer, Climate Change in Australia website.

Bendigo area	Current	2030 RCP4.5	2050 RCP4.5	2050 RCP8.5
Days over 40 °C	1	2-4	3-5	3-6
Days under 2 °C	35	24-29	18-29	15-22

Precipitation

A tendency for reductions in cool season rainfall under enhanced greenhouse conditions has been a consistent result from climate modelling for many years (CSIRO; BoM 2007). This is most important for the southern MDB where cool season rainfall predominates. The process behind this change appears to be essentially a southward shift of mid-latitude weather systems and an expansion of the tropics (CSIRO 2012; CSIRO; BoM 2015; Hope et al. 2015). Warm season simulated rainfall change in southern Australia is less clear and ranges from an increase to a decrease (CSIRO; BoM 2015). In all seasons, natural variability is high relative to the signal and may obscure the forced change for some decades (CSIRO; BoM 2015). Presented below are CMIP5-simulated rainfall changes from CCIA for the two regions most relevant to the MDB.

It should be noted that dynamically downscaled projected rainfall change over NSW is also available from the NSW Government based on the earlier CMIP3 model ensemble (NSW/ACT Regional Climate Modelling (NARCliM) project http://climatechange.environment.nsw.gov.au/Climate-projections-for-NSW) and that these projections lie closer to the wetter end of the range of rainfall change of CMIP5. Dynamical downscaling using the CCAM model reported in CCIA (CSIRO; BoM 2015) also showed this tendency. Grose et al. (2015) has compared the NARCLiM projections with those of CMIP5 and other downscaling for the Central Slopes, and whilst they noted that the fine resolution technique may more reliably reflect topographical influences in some places, the broad trend for a less drying and a more wetting climate in the NARCLiM projections was not well understood and not necessarily to be preferred.

Projected changes in precipitation based on CCIA are tabulated for 2030 and 2050 for southern and northeast portions of the Basin in Table 3 (annual changes) and Table 4 (seasonal changes). Annual average precipitation change in 2030 is -11 to +5% in the south and -13 to +8% in the north. By 2050 these ranges are around -17 to +8% and -16% to +11%. Thus the range of change extends from drying to wetting but with a greater tendency for drying, particularly in the south. Indeed, projected drying is stronger still in the Victorian-only component of the Murray Basin region (Timbal et al. 2016). The wetting case is most evident in the north in summer and autumn (around -25 to +25% in 2050), and the drying case is most evident in spring, especially in the south (around -15 to +10% in 2030 and -30 to +10% in 2050). Forced changes are much smaller compared to natural variability than they were for temperature (see Figure 8 for an example of the time evolution of precipitation in a drying model), with the result that the effect of varying emission scenarios is not strongly evident. Natural variability has probably contributed to the observed cool season rainfall decrease since 1995 already being comparable to the dry end of the projected rainfall change for 2030, although this fact also raises the concern that the models may be underestimating the rainfall response.

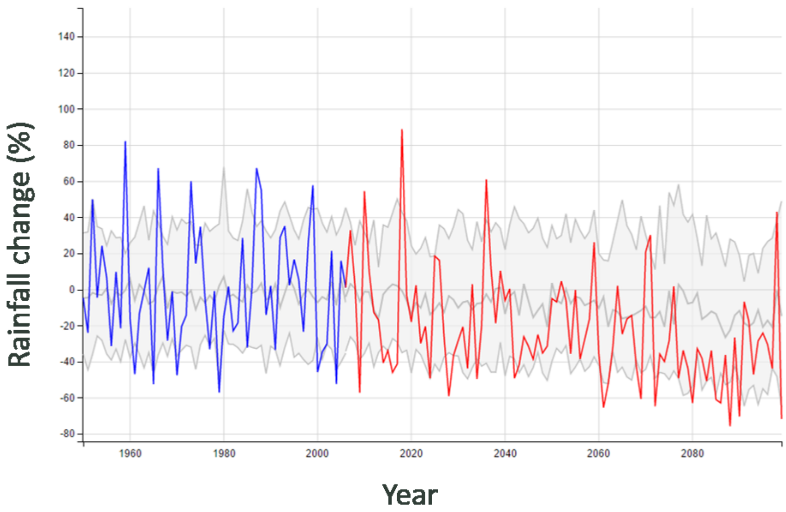

Figure 8. Example of model simulated historical (blue) and projected (red) winter precipitation anomaly (in %) for Murray Basin region from a single global climate model (GFDL-ESM2M model, RCP8.5). Grey envelope indicates results from multiple models. Source: Time Series Explorer, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/climate-projections/explore-data/time-series-explorer/

Table 3: Average annual precipitation change (10th to 90th percentiles) in Murray Basin and Central Slopes in 2030 and 2050 and under RCP2.6, RCP4.5 and RCP8.5. Baseline is 1995 (1986-2005). Source: Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/)

	Region	RCP2.6	RCP4.5	RCP8.5
2030 (2020-2039)	Murray Basin	-11 to +4	-9 to +5	-11 to +5
	Central Slopes	-11 to +8	-11 to +7	-13 to +8
2050 (2040-2059)	Murray Basin	-17 to +5	-13 to +7	-14 to +8
	Central Slopes	-15 to +9	-13 to +7	-16 to +11

Table 4: Average seasonal precipitation change (10^{th} to 90^{th} percentiles) in Murray Basin and Central Slopes in 2030 (2020-2039) and 2050 (2040-2059) and under RCP4.5 and RCP8.5. Baseline is 1995 (1986-2005). Source: Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/)

		Murray Basin		Central Slopes	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
2030	DJF	-15 to +13	-9 to +16	-9 to +16	-12 to +23
	MAM	-24 to +12	-21 to +12	-22 to +19	-17 to +14
	JJA	-15 to +8	-17 to +7	-20 to +11	-27 to +15
	SON	-16 to +12	-17 to +7	-18 to +12	-23 to +12
2050	DJF	-15 to +20	-17 to +14	-9 to +20	-19 to +19
	MAM	-18 to +15	-20 to +20	-21 to +18	-25 to +26
	JJA	-13 to +6	-16 to +9	-21 to +12	-27 to +12
	SON	-24 to +9	-28 to +10	-20 to +13	-31 to +14

Unlike mean rainfall where the direction of change is not clear, magnitude of extreme daily rainfalls is very likely to increase. CCIA concluded for the Murray Basin: “Understanding of physical processes coupled with high model agreement gives high confidence that the intensity of heavy rainfall events will increase” (Timbal et al. 2015), and also drew very similar conclusions for the Central Slopes (Ekstrom et al. 2015). In fact, this tendency applies globally, as shown by the recent IPCC report (IPCC 2013). However, CCIA also concluded: ”There is low confidence in the magnitude of change, and therefore the time when any change may be evident against natural variability, cannot be reliably projected” (CSIRO; BoM 2015). Increased daily rainfall extremes poses the risk of increased flooding and erosion, among other impacts.

On the other hand, changes to meteorological drought occurrence (drought occurrence defined in terms of rainfall deficits) largely follow the projected changes to mean rainfall (increase or decrease, but with decrease more likely). Based on its analysis of the CMIP5 models results, CCIA concluded that: “There is medium confidence that the time spent in meteorological drought will increase over the course of the century under RCP8.5” for the Murray Basin and Central Slopes (Ekstrom et al. 2015; Timbal et al. 2015).

Other variables: Evapotranspiration, soil moisture, snow, fire weather, sea level rise (from CCIA)

Projected warming is associated with increased potential evapotranspiration throughout Australia, including the regions in the MDB. The magnitude of the increase in 2030 is around a 1-6% (CSIRO; BoM 2015; Ekstrom et al. 2015; Timbal et al. 2015).

The increase in potential evapotranspiration results in a tendency for reductions in soil moisture on average in the Basin that are stronger than one may expect from rainfall changes alone (CSIRO; BoM 2015; Ekstrom et al. 2015; Timbal et al. 2015).

Primarily due to increased temperature, fire weather conditions would become harsher. This change is also moderated by rainfall changes, and would be most evident with reduced rainfall (CSIRO; BoM 2015; Ekstrom et al. 2015; Timbal et al. 2015).

Higher temperatures lead a reduced likelihood of precipitation falling as snow, and faster melt of any snow on the ground. CCIA concluded that snowfall and maximum snow depth would decline with high confidence (CSIRO; BoM 2015; Timbal et al. 2015). This would have the effect of shifting the period of peak runoff to earlier in the season in snow-affected catchments.

Sea level rise at the Murray mouth may be estimated from the relevant regional sea level rise projections in CCIA. Projected increase in 2030 (relative to 1995) at Victor Harbour is 0.12 m (0.08-0.16 m) under RCP4.5 and 0.13 m (0.08 – 0.17 m) under RCP8.5 (Timbal et al. 2015). CCIA does not provide regional projections for sea level rise in 2050, but by 2090 it is 0.45 m (0.28-0.63 m) under RCP4.5 and 0.60 m (0.39 – 0.83 m) under RCP8.5 (Timbal et al. 2015).

Wet and dry climate scenarios: Climate analogues

In this section we explore further what the combination of changes to precipitation and temperature may imply for the climates of individual sites in the Basin. The approach used was to select a site of interest and then find locations that currently have the projected future climate for the target site, under the climate scenario considered. This was done using the 'Analogues explorer' on the CCIA website, and analogues were sought based on annual average maximum temperature and precipitation (within tolerances of up to +/- 1 ^{o}C and +/-15%, but usually much less).

Across the two variables, the model range was represented by a hottest and driest case and a coolest (least warming) and wettest case as provided on the CCIA website. The RCP4.5 emission scenario was used for 2030, and the RCP8.5 scenario was used for 2050, noting that results for RCP4.5 in 2050 would lie between these two extremes. The magnitude of the rainfall and temperature changes in these four cases are indicated in the first row of Table 5. Note that these changes are based on individual model results and do not align directly with the 10th and 90th percentile of model ranges provided in the previous section.

It should be noted that these analogue results are to be treated as no more than broadly indicative. Changes in rainfall seasonality are ignored, and for small changes (2030) the signal can be clouded somewhat by the tolerances used.

The resulting climate analogues for range of selected sites in the MDB are listed in Table 5 and mapped in Figure 9. Sites in the Basin 'move' to lower elevation sites further inland and/or to lower latitude (which is generally to the northwest) under the hottest/driest scenario. Under the coolest/wettest scenario, sites 'move' to lower latitude without going further inland (and generally move north-eastward). In the 2050 under RCP8.5, climate analogues may be many hundreds of kilometres away in areas of differing agricultural production and sometimes outside the Basin.

Table 5: Climate analogue sites for nine locations in the Basin under the climate scenarios indicated. Temperature and precipitation changes indicated for each MB (Murray Basin) and CS (Central Slopes). Source: Climate Analogues Explorer, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-analogues/analogues-explorer/)

	Hottest and driest 2030 RCP4.5 MB, +1.1 C, -7% CS +1.1 C, -9%	Coolest and wettest 2030 RCP4.5 MB, +0.9 C, 0% CS. +0.9 C, 10%	Hottest and driest 2050 RCP8.5 MB, +2.1 C, -21% CS, +2.5 C, – 20%	Coolest and wettest 2050 RCP8.5 MB, +1.3 C, 8% CS +2.0 C, 7%
Bendigo	Kyabram	Corowa	Griffith Leeton	Wagga Wagga, Cootamundra
Griffith	Hay, Balranald	Cobar	Ivanhoe	Condobolin
Wagga Wagga	West Wyalong, Condobolin	Parkes Forbes	Griffith, Cobar	Dubbo, Parkes
Forbes	Condobolin	Gilgandra	Nyngan, Cobar	Gunnedah, Scone
Renmark	Port Augusta	Menindee	Leigh Creek	Menindee
Dubbo	Coonamble	Gunnedah	Nyngan Lightning Ridge	Narrabri Moree
Goondiwindi	Roma	Gayndah	Tambo	Collinsville
St George	Charleville	Taroom	Barcaldine	Charters towers Emerald
Moree	Roma St George	Goondiwindi	Tambo Charleville	Gayndah

Wet and dry hydrological scenarios

Any changes to precipitation will drive corresponding changes in runoff, with an amplification factor estimated in Australian conditions to be up to a factor of three (Chiew 2006; Reisinger et al. 2014). The Murray-Darling Basin Sustainable Yields project (SY) (CSIRO 2008b) is still the most up to date source of detailed projections of hydrological conditions in the Basin. The results are summarised in CSIRO (2008b), with more detail of the climate scenarios used in Chiew et al. (2008a) and of the hydrological modelling in Chiew et al (2008b). Related results are also given in the report of the South East Australia Climate Initiative (CSIRO 2012). As well as the primary driver of rainfall change, the SY modelling allowed for the effect of projected increase in potential evaporation, but did not include the possible effect of changes to forest water use (Chiew et al. 2008b). Driven primarily by the tendency for projected rainfall decline, the SY study projected decreases in runoff and water availability in the Basin but with a range extending from increases in their 'wet scenario' to strong decreases in their 'dry scenario'. More details of the wet and dry hydrological scenarios from SY will be presented here, but before doing so, the climate scenarios used in SY need to be assessed in the light of the current regional climate projections (as reviewed above), to see if there is any significant change in their plausibility and representativeness.

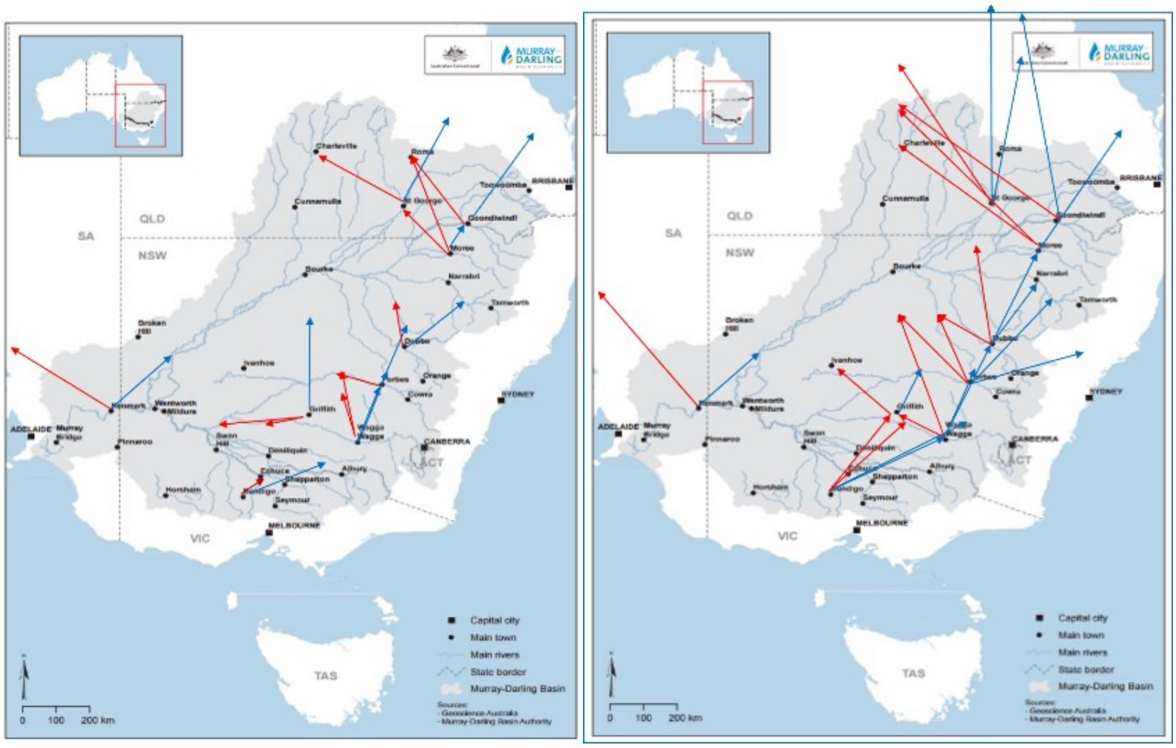

Figure 9: Map depiction of the climate analogues shown in Table 5. Left panel 2030 and right panel 2050. Red arrows hottest and driest case, and blue arrow coolest and wettest case.

The climate scenarios used in SY were based on the earlier CMIP3 ensemble of global climate model results (Meehl et al. 2007), and from these a wet, median and dry precipitation scenario was formed (both at grid points and averaged across the Basin, see Chiew et al. (2008a), based on the 10th, 50th and 90th percentiles of the CMIP3 model results. Figure 10 (CSIRO; BoM 2015) compares the range of the full CMIP3 and CMIP5 model ensembles for precipitation change over Australia. The results from these two ensembles are very similar: a range from wetting to drying (see 10th and 90th percentiles), with a tendency more to drying (see 50th percentiles), and with the wetting case being weaker (and the drying a little stronger) in the southern Basin. However, overall the bias to drying is slightly weaker in the CMIP5 ensemble.

We can also compare the MDB average annual rainfall changes used in SY, with 10th, 50th and 90th percentile rainfall changes from CMIP5 for the Murray Basin and Central Slopes regions from CCIA, see Table 6. The comparison is not exactly like for like (due to the differences in regionalisations and emission scenarios), but the results strongly indicate that were wet and dry scenarios constructed as they were in SY but using the

CMIP5 model ensemble, they would not differ substantially. It should also be noted that projected increases in potential evaporation used in SY of 2-4% in 2030 are also consistent with the CMIP5-based results reported in CCIA (Chiew et al. 2008a; CSIRO; BoM 2015). As noted above, the NARCLiM high resolution downscaled projections based on CMIP3 models were not as dry as in the GCMs, although statistical approaches do not show this tendency (Grose et al. 2015).

Based on the above, it may be concluded that the dry and wet climate scenarios for 2030 as used in Sustainable Yields (CSIRO 2012) are still valid and representative (although the probability of the dry scenario may have declined slightly).

Nevertheless, the need to undertake new hydrological modelling using updated climate scenarios would be justified (depending on the available resources) as new specific questions arise, and as climate projections and hydrological modelling science evolves. In particular, the revised Basin Plan due in 2026 would require hydrological projections to be generated for the period that aligns with its planning horizon which will extend well beyond 2030. There will also be at least another decade of observed climate and hydrological additional data that will need to be considered.

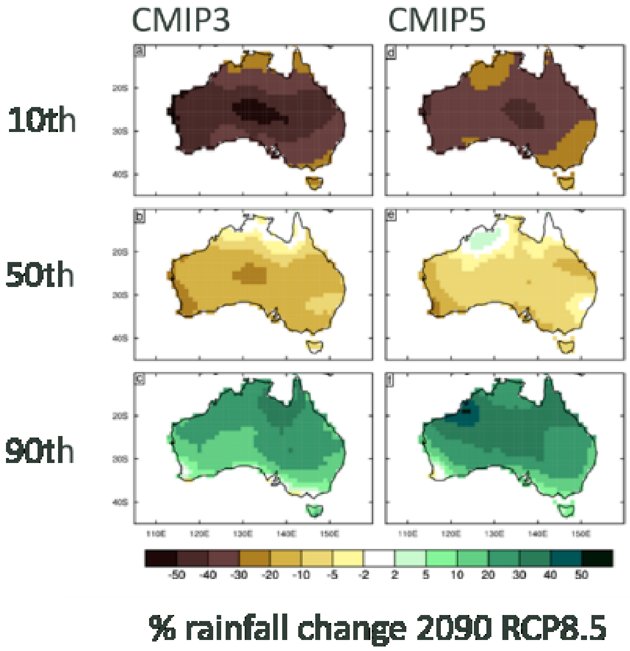

Figure 10: 10th, 50th and 90th percentiles of precipitation change in 2090 (RCP 8.5) for the CMIP3 and CMIP5 model ensembles. Source: reproduced from CSIRO & BoM (2015).

Table 6: Comparison of projected precipitation change in 2030, dry, median and wet cases for the MDB from SY, and 10th, 50th and 90th percentiles for Murray Basin and Central Slopes from CCIA. CCIA results are for RCP8.5, as SY used high emissions to define its wet and dry cases (Chiew et al. 2008a).

	Dry	Median	Wet
MDB average, CMIP3-based (CSIRO 2008b)	-13	-3	+8
Central Slopes, 10th, 50th & 90th percentiles, CMIP5-based (CSIRO; BoM 2015)	-13	-1	+8
Murray Basin, 10th, 50th & 90th percentiles, CMIP5-based (CSIRO; BoM 2015)	-11	-1	+5

Projected changes annual, summer and winter runoff across the Basin in 2030 from SY are presented in Figure 11. Averaged the across the Basin, runoff declines by 33% in the dry scenario and increases by 16% in the wet scenario (CSIRO 2008b). Regionally (Figure 11, top right), the range is around -40% to little change in the southern most catchments of the Basin, and around -30% to +30% in the northern catchments. The dry scenario reduces flow more strongly in winter, and the wet scenario increases flows more strongly in summer (Figure 11, bottom left and right).

Impacts on water availability in each catchment as calculated in SY is indicated in Figure 12. Similar to percentage runoff changes, the southern catchments see little increase in the wet scenario and substantial decreases in the dry scenario. The northern catchments see increases or decreases depending on the scenario. Summed across regions, changes ranges from 11 percent increase (2631 GL/year) under the wet extreme to a 34 percent reduction (7893 GL/year) under the dry extreme climate (CSIRO 2008b). With relevance to the condition of the lower lakes and Murray mouth, estimated end-of-system flows in 2030 assuming current development are an increase of 20% in the wet scenario but a decrease of 69% in the dry scenario (CSIRO 2008a). Crosbie et al. (2010) used the SY scenarios to simulate changes to groundwater recharge in the Basin and found that recharge changes were more biased to increase (stronger increases and weaker decreases) than the surface water changes. More detailed hydrological impact information for these two scenarios may be found in CSIRO (2008b) and Chiew et al. (2008b)

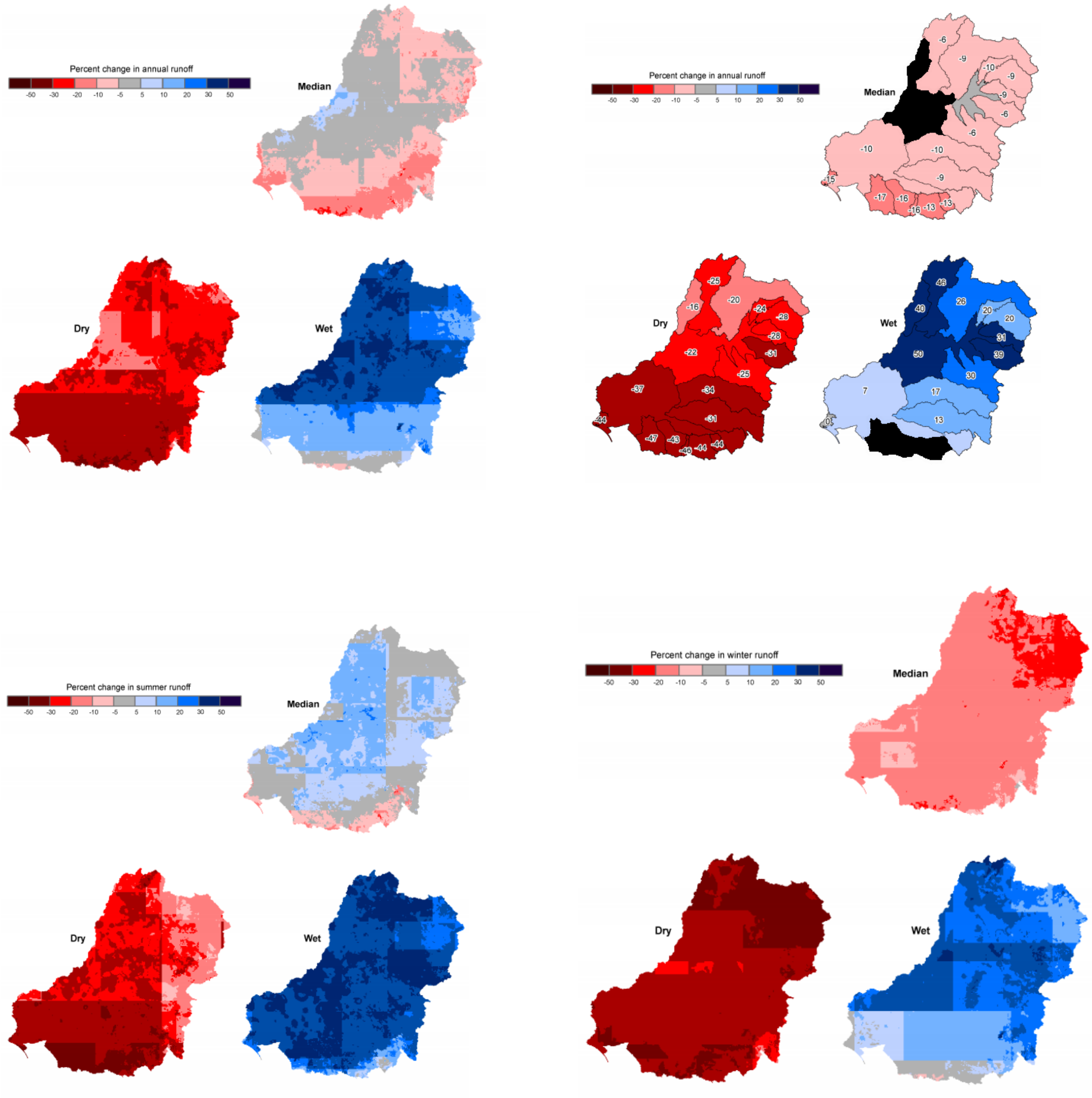

Figure 11: Median, Dry and Wet scenarios from SY for percentage runoff change in 2030: annual gridded data (top left), annual subcatchment average (top right), summer gridded data (bottom left), winter gridded data (bottom right). Source: reproduced from Chiew et al. (2008b).

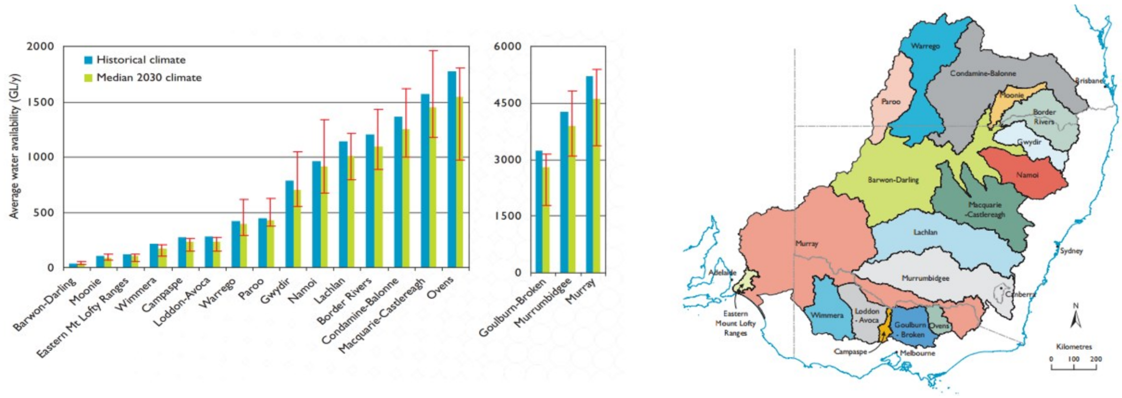

Figure 12 Average surface water availability in GL/year (left) for regions (right) in the MDB. Historical and median future climate for 2030 shown in bars and the wet and dry scenarios by the red bar. Source: reproduced from CSIRO (2008b).

Conclusions

The Murray-Darling Basin area has warmed by around a degree since 1910, and will continue to warm (projected ranges is 0.6–1.5 ^{o}C in 2030 relative to 1995, and by 0.9–2.5 ^{o}C in 2050 without mitigation), with more hot days and fewer cold days. Rainfall is projected to have a tendency to decrease, particularly in the south and in winter, with more time in drought and decreased soil moisture. However, both natural variability and model-to-model difference are large, and both increase and decrease rainfall is possible, particularly in the north. Daily extreme rainfall is projected to increase even when average rainfall declines, with implications for erosion and flooding. Using a climate analogue approach, sites in the Basin 'move' inland/northwest under the hottest/driest scenario and north/northeast in the coolest/wettest scenario. The analogues may be many hundreds of kilometres away and outside the Basin in 2050 under high emissions.

Wet and dry extreme climate scenarios used in Sustainable Yields (CSIRO 2008) were assessed as still valid and representative given latest science, and thus the consequent hydrological scenarios are similarly still valid and representative (although the latest modelling results suggest that probability of the dry scenario may have declined slightly). For the dry scenario there are large reductions runoff and water availability throughout the basin. For the wet scenario there are significant increases in runoff and water availability in the north grading to little change in the south.

Acknowledgements

The author is grateful for valuable discussions regarding this project with Peter Cosier, David Karoly, Celine Steinfeld, Jamie Pittock, Francis Chiew, Michael Grose, John Clarke, and Marie Ekström.

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