MDBA PROJECT MD1523: IMPACTS OF CLIMATE CHANGE – PROJECT GROUP COORDINATOR

DRAFT FINAL REPORT

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1. Executive Summary

Global climate change is well documented through warming of the atmosphere and oceans, sea level rise and changes in the cryosphere over the last 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 last 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 River, the Darling River and the Murrumbidgee River) and contains more than 30,000 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 impacts 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. This paper broadly describes the scope of the MDBA projects, some knowledge outputs to date, areas of knowledge uncertainty, and implications for future research.

This report describes the coordination and knowledge synthesis of four projects conducted under the Murray-Darling Basin Authority’s Risks to Shared Water resources Program. The four projects are:

- Impacts of Climate Change on the People, Communities and Industry of the MDB;
- Impacts of Climate Change on the MDB’s Water Quality;

- Risk of climate change impacts on salinity dynamics and mobilisation processes in the MDB; and
- Impacts of Climate on the Aquatic Ecosystems of the MDB.

The key findings of these projects are:

Impacts of Climate Change on Industries and Communities

Impacts of climate change on irrigated agriculture

The economic impacts of four climate/water scenarios were tested with models. The scenarios were: (a) long term average conditions, (b) CSIRO 2030 medium, (c) 1997-2006 continuation (least favourable) and (d) most dry year of CSIRO 2030 dry (dry-extreme). The latter was an additional scenario to those prescribed in the brief; its purpose was to test extreme impacts.

Overall, the results indicate that only in the most extreme scenario (dry-extreme) does predicted climate change have a major impact Basin wide. However, under the least favourable scenario the impacts are substantial in particular regions. In terms of the least favourable scenario, there is only a moderate change in irrigation water use for the Basin as a whole (13%), but there are large changes in some regions. In particular, the Murrumbidgee, Campaspe and Loddon-Avoca regions suffer 50% or more reductions in water use. In the dry-extreme scenario there is a two thirds reduction in water use by irrigated agriculture in the Basin and the virtual elimination of irrigation in many regions (Murrumbidgee, Murray, Goulburn-Broken, Campaspe and Loddon-Avoca).

The profit declines are much less than water use reductions because the least profitable irrigation activities are eliminated first when water availability is reduced provided that water markets are competitive. Over the entire Basin, net profits decline by about one third in the dry-extreme scenario or about half the percentage decline in water use. Irrigation employment falls by 35% in the dry-extreme scenario and 9% in the least favourable scenario. Irrigation land use change is similar to the changes in water use.

The common denominator of economic models of irrigated agriculture is that reductions in surface water availability are generally expected to be the most significant impact of climate change in the southern Basin. Economic costs (in percentage terms) are likely to be considerably less than the reduction in water availability. The estimated economic impacts of reduced water availability tend to vary substantially across regions, although southern regions are likely to be relatively more vulnerable.

Irrigation farmers can effectively adapt to mild or moderate climate change given unrestricted water markets. As water availability decreases, irrigators apply less water (deficit irrigation) and fallow more land. Provided water markets are unrestricted, reductions in profits are much less than the decline in inflows. In the absence of such trades the decline in net returns is significantly higher.

Irrigation communities dependent on relatively low value uses for water (such as cereals) and pasture and hay will have to adapt to reduced water availability. This may involve switching to higher-value irrigation crops or to crops that are less water intensive, to dryland agriculture, or to alternative economic activities

In terms of economic outcomes, the adverse effects of climate change would be significantly greater if they take the form of more frequent droughts rather than a uniform reduction in inflows.

The Australian agricultural sector is highly adaptive. Relatively low cost adaptation strategies are available for moderate reductions in water availability.

Water trading dampens the impact on gross regional product of water allocation cuts, with the benefits of trading within irrigation districts being greater than those of a further expansion of trade between regions. In large part, this is because of water trade that has allowed water to move from low (such as hay production) to higher valued uses (such as fruit production and viticulture). This is consistent with the findings that, with an optimal allocation of water, substantial reductions in water use for irrigation can occur with only modest reductions in the value of agricultural production.

Policies directed to individuals, such as subsidies for on-farm water use efficiency improvements or payments via LandCare programs, are important for translating community adaptation priorities to on-the-ground responses. Current incremental change should be viewed as an on-going process of on-farm risk management that many farmers practice to respond to climate variability. At least in the short term, such incremental adaptation to climate variability will be the most effective farmer response to climate change.

Impacts of climate change on irrigation communities

There was much less awareness expressed amongst the irrigators, farmers and the growers we engaged with about climate change or the need to begin thinking about a future Basin in that context.

The long period of increasingly adverse drought conditions has meant that farmers and growers are very focused on the here-and-now and giving less attention to long-term planning. After having emerged from a long period of adversity it is not surprising to find that people in the Basin communities are feeling worn down, resource depleted, empty inside with nothing left to call upon and resigned to the easiest or least-worst option. Yet this could be precisely the moment when communities need to be bold and daring to make the big changes. As a result communities might no longer have the adaptive capacity – or at least need this to be re-energised — for transformational adaptations of the scale required in relation to the anticipated changes due to climate change impacts.

The belief that communities do have the capacity, creativity and vision to plan together and make the necessary transformative adjustments for a different but sustainable future is one that will become embedded only after some sustained capacity building within those communities. Community capacity to adapt in anticipation of future long-term climate change has undoubtedly been undermined. A long-term process of community revitalisation is required if Basin communities are to re-gain or replenish the capacity for planned and transformative adaptation that will required as a consequence of anticipated long-term climate change impacts.

Effects of climate scenarios on wheat farming

Five climate scenarios were analysed in a wheat production model. The results of the analysis show climate change impacts are minimal, even with the most extreme scenario where rainfall declines by 30% relative to long-term average in all parts of the Basin. Under this worst case scenario, wheat production falls by only about 10% in most regions of the Basin.

Impacts on dryland farm property values

By contrast to the moderate changes in wheat production, however, the dryland property model predicts large changes for the driest scenario relative to the most favourable scenario. Six regions suffer more than a 50% decline in dryland property values in this scenario: Border Rivers, Gwydir, Namoi, Ovens, Goulburn-Broken and Campaspe with only three regions incurring reductions less than 40% (Paroo, Murray, and Barwon-Darling).

Impacts on tourism

By far the largest climate dependent sector, other than agriculture, is tourism, worth almost $10 billion and employs some 60,000 people. Tourism operators with fixed infrastructure, such as hotels or motels, are particularly vulnerable to climate change if it is detrimental to the local attractions. Operators involved in transportation have more flexibility to shift their business activity to alternative locations. Water-dependent tourism such as that based on recreational fishing or bird watching is most vulnerable to climate change because of their sensitivity to its impacts.

Interactions between plantation forestry and water availability

The area of land forested in the Basin could expand by as much as 45% by 2050 if there were to be afforestation for carbon offsets and production demands. The end-of-system flows across the Basin could be reduced by as much as 19% by 2050 when this afforestation scenario is included, instead of the predicted 11% reduction from climate change alone.

Impacts on indigenous communities

Climate change has occurred at different times during Indigenous peoples history in Australia, but recent anthropogenic-caused climate change is viewed as different and troubling. The pace with which climate change is occurring and its effects combined with the weakened resilience of ecosystems in the MDB (brought about by land clearing, population growth and water resource development) create significant ecological vulnerability that is of utmost concern to Indigenous people in the MDB.

Climate change is viewed as yet another change Indigenous people must adapt to since colonisation**,** one which (combined with a range of social, ecological and economic changes) directly threatens the continuation of their culture and livelihoods. Indigenous peoples are most at risk from climate change where they live on marginal lands and are dependent on natural resources.

The impacts of climate change on Indigenous communities from climate change are not well understood. Existing and potential risks have been grouped into nine categories:

(1) ***predictability*****:** impacts around predictability affect the ability for humans and animals to determine the seasons and can affect survival.

(2) ***species availability and quality***: a lack of predictability can affect the availability and quality of species if for example waterfowl are restricted from breeding if there is no food available.

(3) ***safety:*** the amount of quality water available for consumption may be diminished by climate change and this will impinge on Indigenous human rights to have clean water. Communities will become more susceptible to natural hazards such as bushfire.

(4) ***economic:*** economic impacts from climate change will be very significant for Indigenous peoples in the MDB, given their level of socio-economic disadvantage. Economic risks include: impacts on the customary economy where it affects the harvestable quantity and quality of native flora and fauna and the non market costs to spiritual, cultural and religious values because of environmental degradation; further marginalisation from the economy if policy responses to climate change fail to meaningfully involve Indigenous people; and by creating drought conditions in some regions will reduce agricultural production and the employment of Indigenous people.

(5) ***cultural knowledge and practice***: in creating intense pressure on a vulnerable environment climate change has direct consequences on Indigenous culture. Many participants felt that they would only be able to show their grandchildren flora and fauna in captivity or in pictures because they would no longer be available in the wild. Participants reflected that this would create significant challenges in continuing their culture in its present form.

(6) ***access to land***: access to land may be further constrained by climate change making productive land and water scarce and so may restrict the ability of Indigenous people to access natural resources. There is also a risk that Indigenous people will not be able to participate in carbon and biodiversity markets because of a lack of secure title to land.

(7) ***mental wellbeing***: participants argued that if climate change leads to further degradation of land and water that it will affect the mental wellbeing of Indigenous peoples in the MDB. Mental wellbeing may also be affected by climate change where people's ability to harvest

flora and fauna or their quality of life is affected by drought, increased temperatures and lack of water.

(8) ***health***: the less native flora and fauna people can harvest the more they will rely on store bought food. This has resulted in a proliferation of lifestyle diseases in communities, such as diabetes, cardiac illness and cancer. The second impact of climate change on health is through heat-waves, putting stress on people living with substandard housing, or where there is limited access to good quality, potable water.

(9) ***water:*** participants argued that a major impact of climate change will be a lack of water, whose consequences go to the root of people's survival. The amount of fishing activity has been reduced in places, and there have been increases in algal blooms, due to high temperatures and a lack of flow, which stops people fishing, swimming and drinking water.

The role of Indigenous peoples in restoring the health of land and water was viewed as important in building adaptive capacity in social and ecological systems, and programs such as Caring for Our Country and Indigenous Protected Area schemes could be mechanisms to facilitate adaptation. Indigenous knowledge which enabled Indigenous people to survive and adapt is undervalued but it could be important to meet challenges posed by climate change and foster resilience. It is argued that Indigenous nations themselves are best placed to manage and direct water to places of cultural significance, and to ensure habitats have water in the right season for harvesting flora and fauna—this could include water directed to an area to support bush tucker and medicines or a cultural site, so-called 'cultural flows' (a water access entitlement owned by respective Indigenous nations communally to further their objectives, be it spiritual or economic, ecological or social in nature).

Based on the research, ten key findings are provided that should assist the MDBA and other regional, state and Commonwealth agencies to understand and develop strategies for industries and communities to assist in climate change adaptation.

1) Adaptation is not simply about responding to external climate effects, but is about supporting individuals and communities in their responses to a range of shocks, anticipated and otherwise. It is important to recognise that communities and individuals have already had to adapt to the drought conditions of the past decade.

2) Future engagement by the MDBA will be most needed in regions facing greater exposure to climate change in the southern and upper catchments of the Basin as the effects of climate change vary substantially across the Basin.

3) To assist industries and communities, the MDBA should consider co-ordinating its actions with other organisations (primarily at the state, regional and local level). Guidance should be provided at a local-scale, in terms of what might be expected, to provide assistance for communities to envisage possible futures and responses to climate change, and to build community leadership capacity.

4) Effective engagement by outside agencies such as the MDBA will require support for processes that promote information exchange, knowledge creation and actions across multiple scales and stakeholders within and across communities. Dialogues should be continuous and be long term, be adequately funded, and be part of broader efforts that involve other agencies that go beyond direct water related impacts.

5) Community consultation and communication needs to be reviewed and improved to promote trust between communities and the MDB. A regional community presence demonstrating long-term commitment to key communities could be beneficial, especially if the MDBA considered working through existing networks and locally identifiable community leadership, and not just irrigated agriculture organisations.

6) The MDBA should consider developing a variety of approaches to engagement to ensure that sometimes 'hard to reach' but key community groups, such as youth, feel genuinely part of the process.

7) There is a wealth of knowledge and experience across the Basin, much of which is embedded within industry and civil society organisations, that needs to be acknowledged, given legitimacy and could form the basis of Basin and/or State-focused partnerships.

8) Priorities must be developed, in collaboration with communities in the Basin, as to what issues should be given the greatest attention in terms of climate change. These priorities are unlikely to be the same across communities and will require the communities themselves to be part of the priority-setting dialogues.

9) The multiple issues related to climate change impacts require a shift from 'conventional' to 'adaptive' thinking that highlights difficult trade-offs, engages in long-term thinking, seeks inputs

from outside existing organisational structures in terms of design and implementation, and embraces a feedback and learning process.

10) Despite the predicted effects of climate change not being uniform across the Basin, the concerns among Indigenous people are consistent and are centered around ecological degradation, threats to culture and livelihoods, and greater pressure on individual and community wellbeing.

The level of interconnectivity underscores the need for integrated policy approaches to deal with impacts of climate change and the importance of a whole-of-government approach to climate change adaptation.

Impacts of Climate Change on the MDB's Water Quality

Water quality in the MDB is susceptible to a number of climate change drivers.

The dry extreme climate scenario will directly impact water quality parameters through increased water temperatures and decreased streamflow, which are expected to result in decreased dissolved oxygen, increases in the frequency of algal blooms, thermal stratification in water storages and the concentration of pollutants and salt in the water column as a consequence of increased evaporation and decreased runoff. Impacts from increases in water temperature include decreases in dissolved oxygen concentrations and biochemical oxygen demand, with the reduced capacity of warmer waters potentially resulting in fish kills and the release of contaminants from sediments.

Water quality under the wet extreme climate scenario is expected to lead to increased runoff and hence increased pollutant loads, with increased levels of nutrients, salinity and turbidity. However, dissolved oxygen levels would be expected to increase, and the frequency of algal blooms decline.

Climate change may also result in significant indirect impacts, particularly those related to land use. Changes in water availability will affect land use and vegetation cover in the MDB, which has a large bearing on the quality of runoff. Similarly, changes in rainfall intensity will affect sediment, nutrient and organic matter loads. An increase in blackwater events following flooding may result from reduced dissolved oxygen levels and runoff, combined with increased temperatures.

Climate change is predicted to amplify the key drivers of extreme events, such as air temperature, humidity, rainfall and solar irradiation. This is likely to lead to increased frequency and intensity of extreme events such as: prolonged droughts; bushfires; heat-waves; flooding; and dust storms. Extreme events have a low frequency of occurrence, but when they do occur, they can have major consequences for water quality in rivers and water storages. The water quality impacts can compromise the availability and suitability of the basin's water resources for its beneficial uses, such as aquatic ecosystems, irrigation, potable drinking water supply, agriculture and recreation. The high risk areas with the MDB vary depending on the extreme event. For instance, dust storms are likely to occur in the arid, low rainfall regions. However, their impact on water quality may be far reaching due to the ability of the dust to travel hundreds of kilometres. Another example is bushfires, which present a high risk in forested catchments with high water supply and/or aquatic ecosystem values (i.e. south-eastern basin). Drought can have prolonged landscape scale consequences and present a high risk to all beneficial uses.

The MDB has been afflicted with all these extreme events. Drought has typically been the most damaging for the beneficial uses within the region, particularly in combination with bushfires. However, all extreme events experienced have caused environmental, social or economic challenges for the regions. The natural landscape within the MDB would have evolved resilience to such disturbance regimes. However, with the modifications to the landscape since European settlement and now with the predictions of more frequent and intense climatic events with climate change, the resilience of the waterways may be compromised. This means the impacts to water quality will be more severe and the recovery will be slower.

Good water quality is critical to sustaining beneficial uses within the MDB. Therefore, an understanding of how and where extreme events may compromise water quality is an essential first step towards improving the capability to manage water quality risks under climate change.

Given the influence of land use and vegetation on water quality, changes in policy and management that impact land use (e.g. Sustainable Diversion Limits under the Basin Plan) will need to consider the subsequent impacts upon water quality. Flow regulation and releases may also need consideration, with storage releases offering opportunities for managing streamflow to address pollutant, nutrient and temperature concerns.

Risk analyses for the wet and dry extreme climate scenarios have been undertaken for each MDB region and each extreme event. Examples for the Barwon-Darling Region and extreme drought are shown in Tables 1 & 2.

- **Table 1 Consequences of wet and dry extremes for water quality in the Barwon Darling Region based on analysis of historical data**

Climate Scenario	Water Quality Trajectory	Environmental values (High) -fish, macroinvertebrates -wetlands	Water Supply values (Mod) -irrigation -stock and domestic	Recreational Values (Mod) -primary contact -secondary contact -aesthetic values
Wet Extreme Risks (Med)	↓Algal count ↓pH ↓Salinity **↑Turbidity** **↑Total phosphorus** -Temperature	Extremely high turbidity levels will reduce primary productivity levels, resulting in less food resource for aquatic organisms.	Extremely high turbidity levels may increase drinking water treatment costs.	Extremely high turbidity levels make water undesirable and pose human health risks from associated pathogens.
Dry Extreme Risks (High)	**↑Algal count** ↑pH **↑Salinity** ↓Turbidity ↓Total phosphorus ↑↓Dissolved oxygen -Temperature	Algal blooms and decaying algal blooms lead to oxygen draw down, with potentially lethal effects on aquatic organisms. Increasing salinity levels may go beyond the tolerance levels for some species.	Algal toxins and algal biomass may cause water to be unsuitable for stock and domestic drinking water, and also clog infrastructure for irrigation. Increasing salinity levels also make water unsuitable.	The human health, odour and visual impacts from algal blooms in the river will impact on primary, secondary and aesthetic values.

- **Table 2 Risk analysis for impacts of extreme drought on water quality**

DROUGHT MATRIX	Intensity of Event		
Geographical area of the basin affected	Meteorological Drought. Below average rainfall and increased temperatures persist, but do not have significant impacts on hydrology or runoff in catchment areas. Water quality not impacted significantly due to sustained flows. Hydrological connectivity in streams retained.	Hydrological Drought. Meteorological drought persists, affecting soil moisture and runoff to the extent of reduced water allocations for rural areas, and water restrictions in urban areas. Streams begin to lose connectivity in some areas. Increased risk of algal blooms from loss of flows and rising temperatures. Reduced dissolved oxygen levels. Water remains suitable for ecosystems, stock and domestic and irrigation supply.	Severe hydrological drought. Complete loss of connectivity, drying of ecosystem refuges. Groundwater intrusion and hyper salinity. Water unsuitable for irrigation. Increased algal blooms. Levels of pollutants (chemical and microbiological) toxic to aquatic life and human health. Water unsuitable for ecosystems, stock and domestic and irrigation supply.
South western Basin	**High**	**Very High**	**Very High**
South eastern Basin	**Moderate**	**High**	**Very High**
Northern Basin	**Low**	**Moderate**	**High**
Mid-sections of the Basin	**Low**	**Low**	**Moderate**

The whole-of-system response of Basin regions to climate change still requires further investigation.

Climate change impacts on salinity dynamics and mobilisation processes

Climate change impacts on salinity in the MDB will vary across the different regions of the Basin. This is due to the differing drivers of salt mobilisation, which depend upon variables such as rainfall, landscape type, land use and hydrogeology. River regulation also impacts upon salinity in the Basin, with salinity dynamics also varying between regulated and unregulated streams.

For the northern parts of the Basin, both the dry and the wet climate scenarios are unlikely to lead to significant increases in salt loads. Salt loads from the Darling River pose little threat to the Lower Murray due to the long distances from the northern Basin's salt-generating catchments, and the loss of salt to the floodplain during large flood events.

For the southern Basin, the wet climate scenario forecasts either modest increases or decreases in runoff, with little impact on salinity risks. Under the dry scenario, however, less salt would be expected to be mobilised from irrigated areas as groundwater levels fall and water trading moves water from areas of higher salinity risk to lower risk areas with more highly valued agricultural production. Salt loads from dryland areas will either decrease due to reductions in recharge, or in the case of the Mallee, remain fairly constant. Flood impacts on salinity, particularly from the Mallee floodplains, are expected to decrease with a reduction in rainfall and runoff.

The greatest salinity risk due to climate change is expected to come from the Mallee region under the dry scenario. Rainfall recharge rates are relatively low in the dryland parts of the Mallee, meaning that salt loads are expected to be maintained. Similarly, the high value of irrigated agriculture in the Mallee is expected to mean that even under the dry scenario, water will be traded into the region and rates of irrigation will be maintained. This continuity of salt export, combined with lower flows in the Murray River due to reduced runoff, will mean that in-river salinities will be higher under a drier climate. As has been seen in recent years, extended drought poses a significant threat to salinity in the Lower Lakes. The extent to which salinity is a risk here is largely dependent upon management decisions, such as the Basin Plan.

The management of the Murray River in the future, particularly under the Basin Plan, will mean that river operations decisions will need to carefully account for their impact on salinity in the Lower Murray. This includes river levels, whose elevation in summer has affected hydrological gradients and salt export under low flow events. For the Mallee region, the implication is that water trade will need to be carefully managed and balanced with better efficiencies from irrigated agriculture.

There is currently only a limited understanding of rainfall-driven salt mobilisation and the dilution regimes within the Basin’s tributaries. This, along with the assumptions underpinning salt loads under the dry scenario, will need further investigation. The likelihood of the contraction of irrigation under a drier climate also needs to be investigated, due to the effect on the value of water and returns from horticulture.

Impacts of Climate on the Aquatic Ecosystems of the MDB

Climate change has been identified as having a substantial impact on water availability in the MDB with a suggested decrease in future mean annual rainfall ~2030 relative to ~1990 of about 2 percent in the north of the MDB to 5 percent in the southern regions. The ecosystem drivers that are likely to be influenced by climate change, surface temperature, hydrological alteration and UVB radiation, were reviewed with respect to the international literature.

Aquatic ecosystems are recognised as being particularly sensitive to climate change. Climate change will alter their hydrology and thermal regimes and, given that many freshwater organisms have precise thermal and hydrological tolerances, place them under increasing threat. In simple terms, climate change will increase global temperatures and, through regional changes in precipitation, evaporation and runoff, make some areas wetter and others drier. This will redistribute freshwater systems but dispersal capacity and geographical and human barriers will limit colonisation of new locations.

Amongst the fish of the MDB, some are predicted to increase their range and abundance under climate change scenarios while others will be disadvantaged. Likewise, while the river red gum forests associated with the MDB will be potentially impacted by climate change, black box woodland has the potential to increase its range. Potential decreases in floodplain productivity due to climate change have the potential to filter through the food chain and impact the productivity and breeding success of a range of waterbirds.

Climate change is one of a number of stressors on aquatic ecosystems, but will generally act synergistically with other pressures to enhance losses to biodiversity and ecosystem services.

NRM policy and management measures will be primarily adaptive in the climate change sphere as control over climate variables is beyond local controls. However direct actions to reduce synergistic pressures such as water pollution or extraction will be beneficial. Most climate adaptation actions would be aimed at improving the resilience of ecosystems, for example improving riparian shading of first order streams to reduce in-stream temperatures.

To date the global and MDB literature has been well reviewed and some interpretations advanced for specific MDB species. A modelling approach whereby the climate/water scenarios under consideration can be applied at specific locations within the Basin has been designed and partially tested. The recent Big Dry drought (1996-2009) followed by good rains in 2010 provides a unique opportunity to study the effects of prolonged climate stress and subsequent recovery potential – this should be a high priority for MDBA. A few research providers are beginning to pioneer research on climate impacts on aquatic ecosystems and MDBA should consider how best to interface its policy and management knowledge needs with relevant providers.

Emergent issues in climate change science

Over the last 12 months climate science has faced severe public scrutiny, particularly following the much publicised errors found in the IPCC (2007) report. This has damaged the credibility of climate science in the public's mind, and lowered climate change as an issue of importance across many countries.

In this project some thought has been given to assessing climate science applied to the MDB in terms of the *Best Available Science* tool developed for the MDBA by SKM (Schofield, 2010). The tool is presented in Table 3 below, along with a categorisation of high to low confidence in the science.

Table 1-1 Assessment of MDB climate science (MDB CC) in the *Best Available Science* tool

Scientific Maturity	Scientific reliability				
	Consensus based science	**Peer review**	**Unpublished peer review**	**Grey literature**	**Personal opinion**
Confirmed science	High	High			
Applied science	High	High			
Virtually proven science	High	High	High	Medium	
Reproducible evolving science	High	High	Medium	Medium	
Rationalised science	High (IPCC)	Medium (MDB CC)	Medium (MDB CC)	Low (MDB CC)	
Multi-party scientific judgement	Medium	Medium	Medium (MDB CC)	Low (MDB CC)	Low
Individual scientific judgement			Low (MDB CC)	Low (MDB CC)	Low

Rationalised Science is information derived from reproducible evolving science. However, it uses assumptions, extrapolations, and similar processes in deriving its results and conclusions. In order to reproduce this class, the investigator must have not only the proper skills and the necessary equipment, but must also accept the asserted scientific foundation, assumptions, choice of mathematical processes, default data, and numerous other prerequisites.

It is clear from Table 3 that MDB climate science (MDB CC) is rated low to medium confidence. This is not an indictment of climate science but rather an expression of the complex systems being studied and the strong reliance on computer modelling for future projections, based on a very large number of assumptions.

Perhaps the over-riding 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) who 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 the above quandary, modellers have developed future climate scenarios that capture both a range of future GHG 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.

Some other areas of climate science requiring further attention include:

- Uncertainty in climate change forecasting needs to be addressed more explicitly and communicated more effectively.
- 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.
- The natural variability of the MDB climate, due to a number of regional scale climate 'modes' that affect the climate over weeks, months, seasons, years and decades (e.g. ENSO, IOD,

SAM, IPO/ PDO, STR) are not effectively incorporated in GCMs which limits their forecast ability.

- GCMs do not adequately incorporate a number of GHG feedback mechanisms. Hence current projections are likely to be conservative.
- 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, there is strong evidence they can affect climate outcomes.
- It is proposed here that more emphasis should be placed on observations of climate change in the instrumental and palaeoclimate records as a means of understanding and assessing impacts of past and future climate change, particularly given the limitations on future GCM forecasts and their inability to account for some current observed trends such as autumn rainfall decline.
- Climate change and climate variability are arguably the most important drivers of future change to the natural resources of the MDB and may have significant impacts on industries and communities. Clear, well-argued priorities for research to meet the needs of all sectors of the community should be agreed and financially supported.

2. Introduction

In March 2010, MDBA's Risk Assessment Program engaged SKM to coordinate three research projects investigating the impacts of climate change on Natural Resource Management (NRM) in the MDB, and to synthesise the outcomes of the research (project MD1523). This coordination project builds on a Phase 1 of activity (also coordinated by SKM) that included the commissioning of a series of climate science reviews and preparing a first stage knowledge and policy synthesis.

There three projects being coordinated by SKM are:

- Impacts of Climate Change on the MDB's Water Quality (Project code CD2A);
- Impacts of Climate on the Aquatic Ecosystems of the MDB (Project code CD2B);
- Impacts of Climate Change on the People, Communities and Industry of the MDB (Project code CD2C).

After the commencement of project MD1523, SKM was requested and agreed to co-ordinate an additional project in the climate risks program:

- Risk of climate change impacts on salinity dynamics and mobilisation processes in the MDB (MD1528).

This report describes the activities undertaken in the project coordination process and provides syntheses and commentary on the four projects co-ordinated.

3. Achievement Against Contract Requirements

Table 4 presents a summary of achievements against the contract requirements as expressed in the milestones and described in more detail in the appendices.

- **Table 3-1 Achievement against contract requirements**

Contract Requirement	Achievements
Objective	
To ensure coordination, sharing of work and knowledge, and synthesis of results across four climate risk projects	Project co-ordination has included organisation of an initial joint workshop for knowledge sharing and establishing commonalities to approach, advice on climate and water scenarios, participating in project workshops and teleconferences, responding to specific questions when raised, review of milestone reports and final reports, and resolution of under-performance. Synthesis has included preparing science syntheses for the four projects and an overview of all the MDBA funded research on climate change and its NRM impacts in the MDB.
Deliverables	
A full synthesis report to the MDBA capturing the key results from across the four projects	The synthesis of the four projects is provided in this report.
A presentation of the final synthesis report of the project to the MDBA is required	Presentation will be arranged with MDBA as required.
Specific requirements	
Ensure that all three of the Phase 2 projects use the identical three climate scenarios described in the brief	The same three scenarios have been largely adopted by all projects. SKM's Project Coordinator prepared a discussion paper on the detail and issues surrounding the climate scenarios described in the briefs and gave a presentation on 'current knowledge of climate change in the MDB' (Appendix E) at the initial joint project workshop to inform project teams of the latest climate research. Ongoing advice has been provided by the Program Coordinator since to all projects. At least one project has included an additional scenario, and another project has included the analysis of climate change induced extreme events.
Show how a common analysis of likely climate change impacts on vegetation, water resources and land uses across the Basin,	A common analysis has not been possible (beyond the climate and water scenarios) as the climate change impacts on vegetation, water resources and

Contract Requirement	Achievements
required to underpin each project, could best be undertaken by the group as a whole	land uses across the Basin are subject to ongoing research, poorly understood and either disputed or have high uncertainty. A number of projects funded by the Risks Program are attempting to address some of these questions specifically and it will be an important task of a comprehensive final synthesis to clarify what is known, the certainty of this knowledge and the remaining gaps in knowledge.
Achieve the continued and timely sharing of skills and expertise, and new knowledge as it comes to hand, across the four projects	Sharing of skills and expertise, and new knowledge has occurred to a degree but is naturally constrained by individual projects motivated to deliver on their specific contracts and the day-to-day time pressures facing university researchers in particular. Sharing has occurred mostly through responses to specific questions, identifying opportunities for cross-discussion and through specialist workshops run by individual projects. It is proposed to run a final workshop that will enable a better transfer of information.
Ensure the collation of results from across the four projects so that : (a) the project reports are consistent with each other, and (b) a synthesis report is prepared that provides clear advice to the MDBA about the relative risks due to climate change to water quality, aquatic ecosystems and people, communities and industry within the Basin, and the steps that could be taken to mitigate those risks	Consistency across projects has been encouraged in use of inputs – the same climate scenarios, climate-induced water scenarios and use of MDBA data. While it is not anticipated or a requirement that each project will come up with fully consistent outputs, areas of difference will be identified and discussed at the final workshop. The synthesis has focussed on summarising the climate risk understanding derived from the extensive project reviews, identifying key points for policy and management and remaining gaps. Some ideas on risk mitigation and/or adaptation are canvassed but were not explicitly covered in the project briefs. The work is also placed in the context of all the research and review funded by the MDBA over the last two years, as well as the global, Australian and other MDB climate change research. The confidence in the science is assessed in the *Best Available Science* scheme prepared by SKM for MDBA. Broader issues with climate science are discussed briefly.
Show how the projects extend current	The projects were funded in part as a result of gaps

Contract Requirement	Achievements
knowledge.	identified in the Phase 1 SKM report. It is shown how knowledge has been extended through an overview of where all the MDB climate research has got to so far. This is part of the overview synthesis report. High quality knowledge reviews were emphasised by the Project Coordinator, which will assist in identifying advances in knowledge.
Comment on whether and how the project results can be extrapolated to the whole or other parts of the Basin	All projects have taken a Basin-wide approach, but also focused on higher priority areas of the Basin relevant to the risks involved. The synthesis partially identifies which regions knowledge applies to and any risks/opportunities of extrapolation.
Where appropriate, structure the project so that it may be repeated in future to determine trends over time	Repeatability has been emphasised for all projects and the principles for achieving this were discussed and documented in the first joint project workshop (Appendix A).
Outline the management implications/ opportunities that could arise from the work	Management implications/opportunities have been outlined in the syntheses and will benefit from the final researchers' workshop.
Where appropriate, identify opportunities for further R, D&E that would assist the Authority in meeting its mandate and goals	Opportunities for further R, D&E have been included in the synthesis process and will be discussed at a final joint project workshop.
Identify the main audiences for project outputs and appropriate communications strategies/ opportunities	Communications needs and approaches have not been addressed as the MDBA project manager advised that other mechanisms were being put in place to address this question.
Provide a Plain English summary of the project at its conclusion suitable for a non-technical audience	A Plain English summary is provided for each project in the Executive Summary that can subsequently be used in various communication tasks.

4. Project Coordination

4.1. Initiation Workshop

The Initiation Workshop for the four projects was organised for Tuesday 23 March 2010 with the following objectives:

1. Understanding the background to the Risks Program and any new developments
2. Discuss issues relating to the compressed timelines required by the MDBA
3. Undertake project information exchange
4. Discuss the use of common climate scenarios (as proposed in the project briefs) and the potential for using common risk frameworks
5. Discuss how climate change drivers, including climate parameters, water scenarios and land use responses/changes will be handled in each project
6. Discuss climate and water data requirements and availability
7. Discuss emphasis on clarifying the existing knowledge base in the MDB and internationally where relevant through comprehensive literature reviews
8. Discuss nature of outputs and synthesis products (including data, sites, regions, north versus south basin analyses, GIS, risk colour coding, and journal publications)
9. Discuss and agree on requirements for repeatability of analyses to be conducted at a future time with new information
10. Discuss relationship and value-adding to Basin Planning work.

The workshop Agenda and Minutes are provided at Appendix A. The key inputs and outcomes are described in more detail in the following sections.

4.2. Project synopses

At the outset of the project the Project Coordinator prepared synopses for each of the four projects to assist in sharing information between project teams. The synopses were reviewed by each team leader and then circulated to each team prior to the initiation workshop. The project synopses are presented in Appendix B. Each synopsis covered the following aspects:

- Project title
- Team members and contact details
- Project scope
- Approach and methods
- Climate inputs required
- Other inputs required
- Outputs generated
- Planned deliverables and products
- Communications plan (if available)
- Links to other risk projects
- Links to other MDBA work
- Links to relevant work outside the MDBA.

4.3. Overview of progress of MDBA's climate research and review

As part of the Initiation Workshop, the Project Coordinator presented a summary of MDBA's climate research and review activities over the last 2-3 years. The presentation is included in Appendix C. The overview covered the following activities:

- MDBA Phase 1 climate syntheses (3 reports prepared by SKM)
- Nine climate science reviews commissioned by MDBA
- NCCARF/MDBA climate science workshop (March 2010)
- Water Resources Research Special Edition on climate science in the MDB
- SEACI phase 1
- Climate risk related projects funded by MDBA's Risks Program
- Other climate risk/NRM topics partially covered
- Ideas on where MDBA can go next.

4.4. Summary of current understanding of climate change knowledge in the MDB

The Project Coordinator prepared and presented to the Initiation Workshop a 100 slide presentation representing the current state of knowledge of climate change in the MDB, drawing on recent work funded by MDBA. The full presentation is included at Appendix D. The presentation covers the following topics:

- Climate/NRM issues for policy and management
- Climate observations at global, Australia and MDB scales
- Understanding the observations – causes
- Climate forecasts for temperature, precipitation and runoff
- Alternative approaches to using climate/water scenarios.

4.5. Climate/water scenarios discussion paper

As an input to the Initiation Workshop, the Project Coordinator prepared a discussion paper specifically on the climate/water scenarios required within the project briefs. The full discussion paper is presented at Appendix E. The paper covered three topics:

- Requirements of the brief
- MDSYP climate-water scenarios
- Alternative approaches.

4.6. Initiation Workshop Issues for Discussion Paper

The Program Coordinator prepared a discussion paper covering all the key issues to be discussed at the Initiation Workshop. The full discussion paper is included at Appendix F. The issues covered were:

- Climate scenarios
- Water scenarios

- Land scenarios
- Geographies, regions, sites
- Risk assessments
- Repeatability

Recommendations were provided as discussion starters for most issues.

4.7. Project coordination activities post initiation workshop

The principal activities undertaken in relation to each project are recorded in Table 5 below.

Table 5 Project coordination activities post- initiation workshop

Project	Activity	Comment
Project CD2A: Impacts of Climate Change on the Murray-Darling Basin's Water Quality	Progress reports	Report 1: 20 May 2010 Report 2: 7 June 2010 Report 3: 19 August 2010
	Workshops/teleconferences	Initiation workshop Attended specialist water quality workshop. Participated in 3 project team telephone discussions MDBA presentation
	Variations	Negotiated a major variation to second phase of the project (see Extreme Events report) providing guidance to the project team, culminating in substantial value-adding.
	Reviews	Literature review (draft and final) Final report (draft and final)

	Climate/water scenarios and data requirements	The climate scenarios provided were adequate for the conduct of this project. Data was adequately sourced by the project team.
	Extenuating circumstances	nil
Project CD2B: Impacts of Climate on the Aquatic Ecosystems of the MDB	Progress reports	Report 1: 20 May 2010 Report 2: 7 June 2010 Report 3: 19 August 2010
	Workshops/teleconferences	Initiation workshop. Nil additional (raised issue with project team that Project Coordinator and MDBA staff should have been invited to the project technical workshop)
	Variations	A major variation was enacted for this project, involving the terminating of the project after completion of the second milestone due to poor performance. The Project Coordinator prepared technical assessments of work conducted and advised the project team on additional requirements for fulfilling milestone criteria to an acceptable standard. The Project Coordinator participated in a teleconference with MDBA and the project team leader to discuss underperformance issues and requirements to address them. The Project Coordinator prepared a termination letter for the MDBA to enact.
	Reviews	The literature review was assessed three times by the Project Coordinator before the required standard was achieved. A

		second methodology report was prepared by the project team under guidance of the Project Coordinator and was reviewed as a draft and as part of the final report.
	Climate/water scenarios and data requirements	The project team were conscious of the benefits of receiving updated climate and water scenarios being used for the MDB Plan. However despite many attempts it was not possible to acquire the data in the form and time required. In the absence of MDBA MDBP data, the project team was able to source relevant temperature data and some flow data for specific sites. Example flow modelling – ecological impact assessments were achieved but would require updating and verification prior to publishing.
	Extenuating circumstances	The project team, whilst rated as Australia's premier aquatic ecology group, substantially and inexplicably underperformed, creating a level of angst and frustration for the MDBA and Project Coordinator.
Project CD2C: Impacts of Climate Change on the People, Communities and Industry of the MDB	Progress reports	Report 1: 20 May 2010 Report 2: 7 June 2010 Report 3: 19 August 2010
	Workshops/teleconferences/meetings	Face-to-face meeting with team leader at ANU. Meeting with MDBA specialist staff and the project team leader as additional input to the project
	Variations	Nil

	Reviews	Review draft and final literature reviews and research reports
	Climate/water scenarios and data requirements	The project team was able to acquire MDSYP climate/water scenarios as per project brief. The team also investigated an additional 'extreme dry' scenario to further test the resilience of communities and industries.
	Extenuating circumstances	The written reports combined various aspects of the work into single documents. The Project Coordinator has spent some time disaggregating and re-assembling the reports to make the knowledge more accessible.
Project MD1528: Risk of climate change impacts on salinity dynamics and mobilisation processes in the MDB	Progress reports	Report 1: 20 May 2010 Report 2: 7 June 2010 Report 3: 19 August 2010
	Workshops/teleconferences/meetings	Initiation workshop Face-to-face meetings
	Variations	Nil
	Reviews	Review draft and final literature reviews and research reports
	Climate/water scenarios and data requirements	The project team took a modelling approach to assessing climate-induced salinity risks in some higher risk locations and situations. As such they required the best available flow and salinity data. Due to their close working relationship with MDBA River Operations, the team was able to access flow data and salinity data (the latter

		from BigMod) for specified climate scenarios relevant to the MDBP.
	Extenuating circumstances	Nil

4.8. Emergent issues of climate science arising from the projects

A number of issues of concern in the practice of climate change science in Australia were noted during the conduct of this project. These issues were raised with the MDBA project managers and are discussed briefly in Section 7.

5. Project Synthesis

The four projects co-ordinated under this contract have been synthesised for the purpose of:

- Providing clear plain English summaries
- Clarifying the key messages arising from the work
- Assessing the scientific robustness of the work
- Identifying where knowledge gaps remain

The implications of the projects for management and policy, and recommendations for future actions are presented in section 6.

Each of the four projects was required to address three climate change scenarios. These scenarios are described below, followed by the four project syntheses.

5.1. Climate change scenarios

Issues surrounding the climate change scenarios have been extensively addressed in previous sections. All projects encompassed the scenarios provided in the project briefs as below.

1. A ‘most favourable 2030 scenario’ that is based on a continuation of the long-term (1895 to 2006) averages for rainfall and runoff across the MDB,
2. A ‘medium 2030 scenario’ that is based upon the medium global warming scenario and associated rainfall and runoff described in the CSIRO report *Water Availability in the Murray–Darling Basin* of October 2008, and
3. A ‘least favourable 2030 scenario’ that is based upon the actual climate of the MDB in the period 1997–2006 (this includes 15% less rainfall and 50% less runoff in the southern MDB when compared with the long-term average).

5.2. Impacts of Climate Change on the Industries and Communities of the MDB

5.2.1. Climate change impacts on irrigated agriculture

Irrigated agriculture in the MDB

The gross value of irrigated agricultural production in the Basin was ~ $5 billion in 2005-2006. Irrigated agriculture occupies 2% of farmland in the MDB (farmland covers 84% of MDB) and involves18,000 farm businesses. The largest agricultural water users in the MDB by activity in 2005-2006, in order of importance, were pasture (dairy, cattle and other livestock), cotton, rice, hay, cereals, grapes and fruits and nuts. The gross value of irrigated production by activity, in order of importance, was livestock (dairying, cattle and other livestock), fruits and nuts, cotton, grapes and vegetables. The largest numbers of irrigated farms were located in the regions of Goulburn Broken (2700), SA Murray Darling Basin (2200) the Murrumbidgee (1900) and the North Central (1900).

Effects of the recent (Big Dry) drought

For the period 2002-2007, average annual net inflows in the Murray River totalled 3,986 GL — the lowest recorded for a five year period. In the recent past this has translated into much reduced water diversions by irrigated farmers of between 30 and 50%. Despite reduced water diversions, the proportion of inflows diverted for agriculture in the River Murray increased from less than 50% in the 1980s and 1990s to 76% over the period 2000-2008, as water plans allow for less than proportional reductions in extractions during droughts. If environment water and irrigation water diversions are reduced by the same proportion with climate change, irrigators' income decline would be significantly higher.

The drought reduced production in the driest years (fell by about 30% nationally and 45% in NSW in 2002-2003 drought). In the driest years there have been large falls in the production of annual water-intensive crops, such as cotton and rice, with negative impacts on communities dependent on these farming activities. The losses in irrigation revenue due to climate change occur because of reduced revenues from lower yields due to deficit irrigation, a smaller area in irrigation and because of increased costs of accessing water. The gross value of irrigated agricultural production increased, in nominal terms, by 9% between 2000-2001 and 2005-2006.

Impacts of climate change on irrigated agriculture

The common denominator of economic models of irrigated agriculture is that reductions in surface water availability are generally expected to be the most significant impact of climate change in the southern Basin. Economic costs (in percentage terms) are likely to be considerably less than the reduction in water availability. The estimated economic impacts of reduced water availability tend to vary substantially across regions, although southern regions are likely to be relatively more vulnerable.

Irrigation farmers can effectively adapt to mild or moderate climate change given unrestricted water markets. As water availability decreases, irrigators apply less water (deficit irrigation) and fallow more land. Provided water markets are unrestricted, reductions in profits are much less than the decline in inflows. In the absence of such trades the decline in net returns is significantly higher.

Irrigation communities dependent on relatively low value uses for water (such as cereals) and pasture and hay will have to adapt to reduced water availability. This may involve switching to higher-value irrigation crops or to crops that are less water intensive, to dryland agriculture, or to alternative economic activities

The actual form that climatic changes will take remains uncertain. What is known is that these changes will greatly affect the economic possibilities facing the Basin’s irrigators as well as the range – and type – of adaptive measures available to them. In terms of economic outcomes, the adverse effects of climate change would be significantly greater if they take the form of more frequent droughts rather than a uniform reduction in inflows.

Adaptation in Irrigated Agriculture

The Australian agricultural sector is highly adaptive. Relatively low cost adaptation strategies are available for moderate reductions in water availability.

Water trading dampens the impact on gross regional product of water allocation cuts, with the benefits of trading within irrigation districts being greater than those of a further expansion of trade between regions. In large part, this is because of water trade that has allowed water to move from low (such as hay production) to higher valued uses (such as fruit production and viticulture). This is consistent with the findings that, with an optimal allocation of water, substantial reductions in water use for irrigation can occur with only modest reductions in the value of agricultural production.

Policies directed to individuals, such as subsidies for on-farm water use efficiency improvements or payments via LandCare programs, are important for translating community adaptation priorities to on-the-ground responses. Current incremental change should be viewed as an on-going process of on-farm risk management that many farmers practice to respond to climate variability. At least in the short term, such incremental adaptation to climate variability will be the most effective farmer response to climate change.

Effects of wet and dry climate scenarios

The economic impacts of four climate/water scenarios were tested with models. The scenarios were : (a) long term average conditions, (b) CSIRO 2030 medium, (c) 1997-2006 continuation (least favourable) and (d) most dry year of CSIRO 2030 dry (dry-extreme). The latter was an additional scenario to those prescribed in the brief; it's purpose was to test extreme impacts. Overall, the results indicate that only in the most extreme scenario (dry-extreme) does predicted climate change have a major impact Basin wide. However, under the least favourable scenario the impacts are substantial in particular regions. In terms of the least favourable scenario, there is only a moderate change in irrigation water use for the Basin as a whole (13%), but there are large changes in some regions. In particular, the Murrumbidgee, Campaspe and Loddon-Avoca regions suffer 50% or more reductions in water use. In the dry-extreme scenario there is a two thirds reduction in water use by irrigated agriculture in the Basin and the virtual elimination of irrigation in many regions (Murrumbidgee, Murray, Goulburn-Broken, Campaspe and Loddon-Avoca).

The profit declines are much less than water use reductions because the least profitable irrigation activities are eliminated first when water availability is reduced provided that water markets are competitive. Over the entire Basin, net profits decline by about one third in the dry-extreme scenario or about half the percentage decline in water use. Irrigation employment falls by 35% in the dry-extreme scenario and 9% in the least favourable scenario. Irrigation land use change is similar to the changes in water use.

The medium climate change scenario is very similar to the most favourable scenario.

5.2.2. Impacts of Climate Change on Dryland Agriculture

Over 80% of the land area in the MDB is used by dryland agriculture and generates about $10 billion worth of production in gross value terms. By far the most important rain-fed grain produced in the Basin is wheat that accounts for over half of total area of grains in production and an even greater proportion of the gross value of production. Pastoral production, other than dairying, is dominated by meat cattle of which there were seven million in the Basin in 2006, and also sheep and lambs that numbered about 40 million.

The 2002-3 drought directly reduced GDP by 1%, and a further 0.6% indirectly via negative multiplier effects. The relatively small impact on the overall economy is because agriculture accounts for only 3.6% of Australian GDP.

On-farm case studies show that improvements in water use efficiency through dryland practices such as minimum disturbance planting, improved phase changes in the cropping cycle and fallow management have proven to be profitable and successful responses to climate change. Allowing for earlier planting and varying the cultivars may even generate yield benefits for wheat because of CO_2 fertilisation. Stokes and Howden (2010) emphasise that the Australian agricultural sector is highly adaptive. At least in the short term, incremental adaptation to climate variability will be the most effective farmer response to climate change. While stressing the importance of autonomous adaptation assistance from government and industry institutions is also required. One of the greatest barriers to adaptation is uncertainty over the effects of climate change.

Effects of climate scenarios on wheat farming

Five climate scenarios were analysed in a wheat production model:

1. The long-term average rainfall and temperature over the period 1895-2006.
2. The short-term rainfall over the period 1997-2006 combined with the long-term temperature over the period 1895-2006. This scenario is designed to isolate the causal effect of recent rainfall patterns *relative* to long-term rainfall alone, since temperature has increased significantly from the long-term average.
3. A modified version of scenario 1, where rainfall is reduced from between 2% by 5% from the long-term average. The reduction occurs by a linear gradient from north to south of the basin.
4. A modified version of scenario 1, where rainfall is reduced by 15% from the long term average everywhere in the basin.
5. A modified version of scenario 1, where rainfall is reduced by 30% from the long term average everywhere in the basin.

The results of the analysis are presented relative to the most favourable scenario. The effects are minimal, even with the most extreme scenario where rainfall declines by 30% relative to long-term average in all parts of the Basin. Under this worst case scenario, wheat production falls by only about 10% in most regions of the Basin.

Climate change impacts on dryland farm property values

The models suggest only moderate change in values except in the most extreme and driest scenario. By contrast to the moderate changes in wheat production, however, the dryland property model predicts large changes for the driest scenario (5) relative to the most favourable scenario. Six regions suffer more than a 50% decline in dryland property values in this scenario: Border Rivers, Gwydir, Namoi, Ovens, Goulburn-Broken and Campaspe with only three regions incurring reductions less than 40% (Paroo, Murray, and Barwon-Darling).

5.2.3. Climate change impacts on Tourism

By far the largest climate dependent sector, other than agriculture, is tourism. Overall, there were over 43 million visits to various parts of the Basin in 2008/2009 with 98% of these visits undertaken by Australian residents. These visits generated turnover worth almost $10 billion and employed, in total, some 60,000 people in the tourism sector.

Tourism operators with fixed infrastructure, such as hotels or motels, are particularly vulnerable to climate change if it is detrimental to the local attractions. Operators involved in transportation have more flexibility to shift their business activity to alternative locations. Water-dependent tourism such as that based on recreational fishing or bird watching is most vulnerable to climate change because of their sensitivity to its impacts.

If climate change encourages Australians to holiday in more southerly latitudes rather than in the tropical north this may benefit some locations within the Basin.

5.2.4. Climate change impacts on forestry

Forests occupy some 23 million ha of the MDB or about 20% of the total land area.

Native floodplain forests, such as River Red gums, are threatened with reduced water availability that may arise with climate change.

Climate change and mitigation polices that may be implemented by Australia may encourage afforestation. The area of land forested in the Basin could expand by as much as 45% by 2050 if there were to be afforestation (one scenario). The end-of-system flows across the Basin could be reduced by as much as 19% by 2050 when this afforestation scenario is included, instead of the predicted 11% reduction from climate change alone.

5.3. Climate change impacts on communities

5.3.1. Climate change impacts on irrigation communities

Farming culture

The irrigation industry is highly differentiated, localised and complex. Variability in approach between each of the states makes it difficult to conceive of it as a single industry. Farmers inherit a sense of stewardship; farming defines them as a person; it is what they would expect their children to be.

Understanding of water and environmental issues

There is an acceptance that the plentiful supply of water (in the past) meant there had been little awareness of just how precious it was as a resource. Contrary to agency views, industry stories were more about a lack of awareness that water was a scarce or precious resource — it was just 'water' and it was plentiful.

There is an overall awareness that the Basin is facing a future with less water. Water security was felt to be the key issue. The environmentally fragile state of the Basin was well recognised, as was the need to divert more water and develop more efficient and effective means of using water to ensure its protection and sustainability. There was much less of an agreement on the levels of water needed to meet such requirements, or where the water should come from. There was also a minority view expressed that the environment should have to make the same kind of adjustments as those of the farmers and growers.

Thoughts about the MDBA role/Basin Plan

There was an acknowledgement that the MDBA had the responsibility to determine SDLs and that irrigators would have to adapt to whatever is set by the new limits. However, there is an expectation that new diversion limits would *not* represent a major change. There is also an anxiety that the Draft Plan would attempt be restore the environment to a pre-modern state.

Thoughts about climate change

There was much less awareness expressed amongst the irrigators, farmers and the growers we engaged with about climate change or the need to begin thinking about a future Basin in that context. Beyond such water-dependent industries there was greater awareness.

Impacts of recent drought in relation to addressing future issues

The recent prolonged and continuing drought in the Southern part of the Basin has had a profound impact on Basin communities. The drought period is sharply felt in relation to the times of plenty over the previous fifty years (1950-2000) during which there was significant expansion and technological advancement in irrigated agriculture. Such conditions of variability, especially during long periods of increasingly adverse conditions, also mean that farmers and growers are very focused on the here-and-now and giving less attention to long-term planning. While responding to conditions of severe drought the industry also faced other global market pressures to be competitive.

After having emerged from a long period of adversity it is not surprising to find that people in the Basin communities are feeling worn down, resource depleted, empty inside with nothing left to call upon and resigned to the easiest or least-worst option. Yet this could be precisely the moment when communities need to be bold and daring to make the big changes. Basin communities may be exhausted – physically, emotionally, financially — with depleted capital by having spent so much time making small-scale adaptations in response to on-going challenges. As a result communities might no longer have the adaptive capacity – or at least need this to be re-energised — for transformational adaptations of the scale required in relation to the anticipated changes due to climate change impacts.

Adaptive capacity

Basin communities and the irrigated agriculture industries in particular have a self-perception of having high levels of adaptability. The idea that adaptation was something that needed to be introduced from the outside was therefore quite at odds with the insights we gained about how Basin communities perceive themselves. Participants argued that significant efficiency gains were evident in relation to growers' changing practices. The perception of an efficient and adaptive industry was usually restricted only to those in the particular catchment, or perhaps the State.

The actual decisions about how to adapt on a particular farm or orchard in the most efficient manner rests with individual families to an extent no longer evident in other sectors. Years of making small-scale adaptations can lead to a situation that would not have been chosen had decisions been made through a planned and thoughtful process focused on the most desirable outcome in a certain period of time in which various options are carefully weighed and assessed against a set of well-chosen criteria. Such adaptations as a response to immediacy are not always small-scale but indeed can be significant in terms of long-term impact. These are often risky decisions, sometimes borne out of desperation, and there is always the danger that they will regret making them partly because the alternative options might have been better ones but especially if the situation begins to return to something like normality, by which time it might be too late to reverse the process.

Adaptive capacity in anticipation of long-term or permanent change first requires an acceptance that how things have been will not be able to continue no matter what.

There is recognition that the capacity for change and adaptation is not distributed equally. Some adapt by acquiring new skills, such as IT and computing, or expanding their knowledge about crops and farming techniques.

Government funded water efficiency infrastructure funding

The idea of supporting further water efficiency infrastructure improvements was not always welcomed as some perceived it to be a reward for those who had not yet become efficient and penalises those who had already made water efficiency investments.

Government funded water buy-backs

Water buy-backs policies were seen both as unjust in themselves and as having long-term negative impacts on the agriculture industry and affecting its capacity to adapt. *'The buy-out affects* *everyone … fixed costs are going up as more people fall off, what was a community asset … communities are being destroyed. The buy-back scheme penalises early adaptors and efficient farmers whilst compensating those that were unviable anyway'.*

Stress on Individual Lives

Coping with prolonged conditions of adversity places a major burden on those with the responsibility for making the necessary adaptations with survival as the bottom line. We were struck by how much of this responsibility fell on individual farming families and of the accumulated impact. Joint or shared responses will always be limited.

With young people increasingly seeing their futures elsewhere, not just in relation to the industry but also the region, there were anxieties expressed both about the impact of those young people moving away and the employment prospects of those who remain.

There was little prospect of being able to sell the farms to newcomers as set up costs made this prohibitive for many. Whereas previously off-farm income had been a supplement to family income, increasingly it is the primary source.

There is an increasing incidence of domestic violence and increasingly levels of visible poverty.

Overall, men are perceived to react by withdrawing and being reluctant to discuss how they were coping with the stress whereas women were more likely to come together, share their experiences and the pressures they felt, provide support for others and make it their business to look out for and be responsive to those who were struggling at any point in time. Despite such efforts the level of stress amongst women was perceived to be on the increase.

Community Stress

When it comes to water management the community is no more than a simple aggregation of everyone who lives there. There was little evidence of on-going dialogue across networks. The research also identified a strong sense of disengagement when it comes to discussing water sustainability and climate change. The comment that, *'the area has been meeting'd out'* was a common refrain. It was now exceedingly difficult to drum up any enthusiasm for such events.

Overall this apparent reluctance to engage in public debate on a matter of immense importance for Basin communities should be a cause for concern and perhaps indicative of a level of community stress. There are many stories to tell. Insufficient effort has been made to really engage with young people. There are growing numbers of in-coming migrants, often refugees, to centres such as Shepparton and Renmark who need greater recognition.

Some underlying tensions exist between those referred to as 'environmentalists' and the farming communities. Also tensions exist between different types of farming such as between some dryland farmers and potato farmers. There were also strongly expressed negative views in relation to other communities. There are tensions between these rural communities and the urban centres within their own states.

Looking to the Future

All is not doom and gloom within Basin communities. As already indicated there is plenty of energy and vitality to be found amongst those local groups concerned with long-term sustainability. Other more specific suggestions included solar energy; the harnessing of natural resource power for energy generation; the development of more 'Transition towns' away from oil-based economies; opportunities to develop crop varieties and intensive horticulture; development of local tourism; and compulsory acquisition of stranded assets. There is a willingness to look to a different future but also an anxiety, in seeking external guidance, about a community capacity to determine that future.

The belief that communities do have the capacity, creativity and vision to plan together and make the necessary transformative adjustments for a different but sustainable future is one that will become embedded only after some sustained capacity building within those communities. Community capacity to adapt in anticipation of future long-term climate change has undoubtedly been undermined. A long-term process of community revitalisation is required if Basin communities are to re-gain or replenish the capacity for planned and transformative adaptation that will required as a consequence of anticipated long-term climate change impacts.

5.4. Climate change impacts on Indigenous communities

Across the northern and southern MDB, there are more than 30 diverse Indigenous nations, each with a traditional connection and a range of inherited cultural responsibilities to land and water that are spatially bound. Rivers and wetlands are central to Indigenous livelihoods, cultural and spiritual life, and customary economy in the MDB. Hunting and gathering flora and fauna around aquatic systems in the MDB, in particular fishing, has sustained populations for millennia and continues to be important to the Indigenous customary economy. Indigenous people have unique rights and interests to water that are customary, spiritual and economic in nature, and these have to some extent been recognised by states such as NSW and Queensland, and in national water reform. However Indigenous people in the MDB have narrow statutory rights to land and resources. About 0.2% of land in the MDB is Indigenous owned.

Indigenous people often feel disengaged from natural resource management activity in the MDB and are seeking more meaningful involvement in land and water management.

Climate change has occurred at different times during Indigenous peoples history in Australia, but recent anthropogenic-caused climate change is viewed as different and troubling. The pace with which climate change is occurring and its effects combined with the weakened resilience of ecosystems in the MDB (brought about by land clearing, population growth and water resource development) create significant ecological vulnerability that is of utmost concern to Indigenous people in the MDB.

Indigenous people believe that the level of deforestation and water resource development in the MDB make it more susceptible to drought. This is consistent with the scientific findings of McAlpine et al. (2007) who identify a link between land clearing and reduced precipitation in localised settings in eastern Australia. Many Indigenous people believe that local land management practices are a far more important cause of variability. Deforestation was viewed as a key cause of climate change in the MDB with many participants seeing this as drying out the land and not attracting precipitation. Indigenous people have seen changes in seasons, water availability and temperatures, which have impacts on Indigenous livelihoods, the customary economy as well as the broader economy.

Climate change is viewed as yet another change Indigenous people must adapt to since colonisation**,** one which (combined with a range of social, ecological and economic changes) directly threatens the continuation of their culture and livelihoods. Indigenous peoples are most at risk from climate change where they live on marginal lands and are dependent on natural resources.

The impacts of climate change on Indigenous communities from climate change are not well understood. Existing and potential risks have been grouped into nine categories:

(3) ***predictability*****:** impacts around predictability affect the ability for humans and animals to determine the seasons and can affect survival.

(4) ***species availability and quality***: a lack of predictability can affect the availability and quality of species if for example waterfowl are restricted from breeding if there is no food available. While the creation of dams and weirs and poor water quality has had a significant impact on the availability of flora and fauna, drought and variable weather patterns is an equally significant stressor. This too has an effect on cultural knowledge and practices where these are related to species migration (such as the Brolga) or in hunting and gathering. Indigenous people grow little food of their own.

(3) ***safety:*** the amount of quality water available for consumption may be diminished by climate change and this will impinge on Indigenous human rights to have clean water. The concern about access to water is especially troubling as many Indigenous communities are often away from town services and infrastructure in the MDB. Communities will become more susceptible to natural hazards such as bushfire.

(4) ***economic:*** economic impacts from climate change will be very significant for Indigenous peoples in the MDB, given their level of socio-economic disadvantage. Economic risks include: impacts on the customary economy where it affects the harvestable quantity and quality of native flora and fauna and the non market costs to spiritual, cultural and religious values because of environmental degradation; further marginalisation from the economy if policy responses to climate change fail to meaningfully involve Indigenous people; and by

creating drought conditions in some regions will reduce agricultural production and the employment of Indigenous people.

(5) ***cultural knowledge and practice***: in creating intense pressure on a vulnerable environment climate change has direct consequences on Indigenous culture. Many participants felt that they would only be able to show their grandchildren flora and fauna in captivity or in pictures because they would no longer be available in the wild. Participants reflected that this would create significant challenges in continuing their culture in its present form.

(6) ***access to land***: reduced access to land is a major issue among Indigenous people in the MDB who hold little tenure in the region. Access may be further constrained by climate change making productive land and water scarce and so may restrict the ability of Indigenous people to access natural resources. There is also a risk that Indigenous people will not be able to participate in carbon and biodiversity markets because of a lack of secure title to land.

(7) ***mental wellbeing***: participants argued that if climate change leads to further degradation of land and water that it will affect the mental wellbeing of Indigenous peoples in the MDB. The participants reasoned that their identity is intertwined with land and water - where it is unhealthy they too feel this. Mental wellbeing may also be affected by climate change where people's ability to harvest flora and fauna or their quality of life is affected by drought, increased temperatures and lack of water.

(8) ***health***: the less native flora and fauna people can harvest the more they will rely on store bought food. This has resulted in a proliferation of lifestyle diseases in communities, such as diabetes, cardiac illness and cancer. The second impact of climate change on health is through heat-waves, putting stress on people living with substandard housing (without insulation and air-conditioning), or where there is limited access to good quality, potable water.

(9) ***water:*** participants argued that a major impact of climate change will be a lack of water, whose consequences go to the root of people's survival. The amount of fishing activity has been reduced in places, and there have been increases in algal blooms, due to high temperatures and a lack of flow, which stops people fishing, swimming and drinking water.

These impacts are interdependent reflecting the level of connectivity in the MDB and the need for integrated policy approaches to address impacts. If conditions were to improve some participants felt the landscape would regenerate. Others felt that the ecological degradation is irreversible.

The role of Indigenous peoples in restoring the health of land and water was viewed as important in building adaptive capacity in social and ecological systems, and programs such as Caring for Our Country and Indigenous Protected Area schemes could be mechanisms to facilitate adaptation.

Indigenous knowledge which enabled Indigenous people to survive and adapt is undervalued but it could be important to meet challenges posed by climate change and foster resilience.

It is argued that Indigenous nations themselves are best placed to manage and direct water to places of cultural significance, and to ensure habitats have water in the right season for harvesting flora and fauna— this could include water directed to an area to support bush tucker and medicines or a cultural site, so-called ‘cultural flows’ (a water access entitlement owned by respective Indigenous nations communally to further their objectives, be it spiritual or economic, ecological or social in nature).

MLDRIN (2003) posits that cultural and spiritual values should be given equal footing to economic values in policy considerations. However a tension in the different worldviews and values on water use is recognised.

In identifying key sites or values Indigenous peoples in the MDB felt that all the land and water is sacred and there are spiritual connections among all Indigenous peoples throughout the MDB that must be protected. Identifying particular sites or values to be protected was counter-productive and unhelpful, and contrary to Indigenous perspectives. River Red Gums were identified by participants as important to be protected because of their aesthetic and spiritual values.

Carbon trading and Bio-Banking were seen by some participants to offer potential economic opportunities from climate change to Indigenous peoples in the MDB. Other participants viewed these as mere short term gains which did not offset the destructive consequences of climate change. Building awareness on the effects of climate change in a meaningful and relevant way at local levels is crucial to improving the adaptive capacity of Indigenous peoples in the MDB.

5.5. Impacts of Climate Change on the Murray-Darling Basin's Water Quality

5.5.1. Surface Water Quality

Land Use and Hydrological Drivers of Surface Water Quality

One of the most important drivers of surface water quality is land use (Quinn et al., 1997; Baker, 2003). The key land use factors affecting surface water quality are:

- Extent of native vegetation and riparian zone clearing (Bunn et al., 1999; Rutherford et al., 2004);
- Intensity of agriculture and agricultural practices (Sauer et al., 1999; Young and Huryn, 1999; Byers et al., 2005); and
- Density of human population, urbanisation and effluent disposal practices (Brabec et al., 2002; Walsh et al., 2005).

For catchments dominated by agricultural land, soil erosion is a major source of sediments, nutrients and pesticides in surface water. These are all important water quality indicators, as well as being important drivers of other water quality considerations, such as outbreaks of blue-green algae. The influence of these non-point sources of contamination increases significantly after heavy rainfall, with increased runoff carrying greater quantities of these contaminants into surface water systems.

The other major driver of water quality is catchment hydrology, although the relationship between hydrology and water quality is more complex than that of land use. Characteristics which have a direct impact upon water quality are:

- Source of water (i.e. groundwater, surface runoff, snow melt; irrigation transfers, flow releases from dams, stormwater, point sources);
- Flow impoundments (i.e. weirs, dams, diversions); and

- Flow regime (i.e. frequency and timing of freshening flows, high flows, low flows and cease-to-flow events, river connectivity) (Poff et al., 1997; Richter et al., 1997).

Good water quality typically is supported by a variable flow regime whereby each flow component fulfils particular functions to restore or maintain water quality. Seasonal variations play an important role in maintaining water quality, and the relationship between source, impoundments and flow regime can have a significant impact. Flows also have an influence on water temperature, which itself is an important driver of water quality. Algal growth, decreased dissolved oxygen, metal concentrations and taste and odour problems are all potential consequences of changes in temperature or thermal stratification.

Climate Change Impacts on Surface Water Quality

Climate change has varying impacts across the Murray-Darling Basin, particularly in the way it affects rainfall and runoff. Reductions in rainfall in most arid, semi-arid and temperate regions are expected to be accompanied by an increase in the intensity of rainfall events (Pittock, 2003; Dunlop and Brown, 2008). However, there is still some debate surrounding this impact of climate change; Verdon-Kidd (2009) notes that there has in fact been a decrease in the intensity of rainfall events during the recent drought. Air temperatures are rising due to the Enhanced Greenhouse Effect, leading to increasing water temperatures. Water quality will therefore be directly affected by air temperatures, as well as indirectly by rainfall, runoff, and land use changes driven by altered temperatures and rainfall.

<u>Direct Impacts</u>

Increased air temperatures will lead to the earlier onset of thermal stratification and delayed mixing of the water column in water storages (Poff et al., 2002). This is expected to exacerbate problems relating to algal blooms, anoxic water, dissolved metals (iron and manganese), foul odour and taste and downstream thermal pollution. Rising temperatures will also increase the rates of nutrient release from sediments (leading to increased eutrophication), while decreases in runoff will increase water clarity and light penetration, further increasing water temperatures and facilitating algal blooms.

Increases in air temperature will also reduce the amount of oxygen dissolved in water. This will affect the survival of fish and macroinvertebrates, which will have flow on effects for other aquatic biota. Dissolved oxygen is also important for a range of geochemical processes, and a reduction in dissolved oxygen can result in the release of nutrients and heavy metals from sediments. Increases in water temperatures may also impact thermally sensitive fish and macroinvertebrates if temperatures increase above species' limits of thermal tolerance. Some species may become locally extinct, cold water species may be restricted to certain river reaches, and high temperatures may benefit exotic species such as carp.

Increased temperatures will drive increased rates of evaporation, which will impact water quality due to the concentration of pollutants. This will affect pollutants such as salt, metals, pesticides and nutrients in the water column. Furthermore, reduced stream flows from a decrease in rainfall are likely to cause the accumulation of some pollutants, potentially affecting ecosystems, human health, water system reliability and water treatment costs.

Indirect Impacts

Changes in rainfall and rainfall intensity, with its subsequent impacts on runoff and stream flow, will have a number of secondary impacts on water quality. Extreme rainfall events are forecast to become more frequent in wetter regions, leading to higher sediment, nutrient and organic matter loads from eroding soils. Increased acidity is also likely in the Murray Region, where changes in flow regime and wetting and drying cycles will affect known acid sulphate soils. On the other hand, an overall decrease in rainfall and runoff can potentially increase river salinity levels in the Basin, with less water available for diluting saline groundwater and increased evaporation compounding salt concentrations.

Reductions in runoff can cause the longitudinal fragmentation of the river channel, preventing the normal transport of nutrients and organic carbon (Bond et al., 2008). Combined with expected increased temperatures and lower levels of dissolved oxygen, this increase in organic carbon can increase the frequency of blackwater events. Blackwater events cause deoxygenation of the water column, and the release of tannins at toxic concentrations, leading to fish kills and other ecological impacts.

The effects of climate change on vegetation and land use in the Murray-Darling Basin will also drive changes in the Basin's water quality. Limitations of the availability of water may mean that some existing agricultural practices and properties will no longer be viable in parts of the Murray-

Darling Basin. The agricultural sector will also continue to move to more sustainable farming and water conservation practices, changing the way land is used, with implications for water quality.

Water quality – climate change relationships

Water quality trajectories and associated impacts from climate change can be understood by identifying how each parameter is affected by climate, as shown in Table 3 below.

Table 5-1 Drivers and consequences of changes to each water quality parameter

Parameter	Drivers	Consequences
Dissolved oxygen	Temperature Land use Stream flow	Fish kills Water treatment issues Release of contaminants
Nutrients	Land use Floods	Algal blooms Aquatic weeds
Turbidity	Land use Floods	Water treatment issues Unsuitable for recreation
Salinity	Water balance Stream flow	Unsuitable for irrigation Unsuitable for drinking
Water Temperature	Air Temperature Stream flow	Thermal stratification Increased rates of ecosystem processes Thermal intolerance of fauna
pH	Stream flow – wetting and drying cycles of wetlands Land use – mining	Unsuitable for recreation Unsuitable for drinking Unsuitable for irrigation
Biochemical Oxygen Demand	Land-use Stream flow	Fish kills Water treatment issues Release of contaminants

Effects of the Dry Extreme Climate Scenario

Under the dry extreme climate scenario considered for this project, water availability in the northern Basin is expected to decrease by 26-29% for all regions except the Paroo (which is expected to experience a 16% reduction in water availability). The southern Basin, however, is expected to experience much greater reductions in runoff, with some regions expected to experience reductions in water availability in excess of 50%. Combined with expected increases in air (and hence water) temperatures, this reduction in runoff and stream flow is expected to lead to:

- Increased water temperatures
- Increased salinity levels
- Increased frequency of algal blooms
- Decreased dissolved oxygen levels
- Decreased turbidity
- Decreased nutrient levels (assuming there are no significant point sources of nutrients)

Effects of the Wet Extreme Climate Scenario

The wet extreme climate scenario used in this project has rainfall in the northern Basin increasing significantly, with increases in water availability varying between 18% and 49%. This is in stark contrast to the southern Basin, where water availability is expected to experience only minor increases or decreases in each region. Where rainfall and runoff increase, water quality is expected to be driven by increased pollutant loads, leading to:

- Decreased water temperature
- Dilution of river salinity (although greater groundwater salt discharge)
- Decreased frequency of algal blooms
- Increased levels of dissolved oxygen
- Increased turbidity
- Increased levels of nutrients.

5.5.2. Impacts of Climate Change on Groundwater Quality

Water Table Dynamics

The change in water table levels is one of the primary drivers of groundwater quality. In unconfined aquifers, the water table represents the gravitational head of water that ultimately drives groundwater into streams, where surface water – groundwater connectivity occurs. The location of the water table with respect to soil salt storages and its depth below ground surface (and hence proximity to fluxes of agrichemicals) are also important determinants of groundwater quality.

Changes in water table levels are associated with changes in land use and climate. In dryland areas, dryland salinity is attributed to the replacement of perennial vegetation with annuals, resulting in increased groundwater recharge. For water tables in irrigation areas, increased infiltration and recharge lead to increases in the elevation of water tables.

Exchange of atmospheric water with groundwater can occur via infiltration of rainfall or snowmelt through the soil profile to recharge groundwater, and via evapotranspiration. Evapotranspiration. includes direct evaporation of shallow groundwater and transpiration by vegetation. Groundwater may also flow into streams, springs, wetlands, oceans, or be extracted via groundwater pumping for human use.

Impacts of climate change on groundwater quality

Under the *wet climate scenario,* increasing rainfall and rainfall intensity will leach additional contaminants (e.g. salt, trace metals, pesticides) from soils into aquifers. Under the *dry climate scenario* recharge is projected to decrease, and water quality may improve or decline depending on the combined effects of reduced leaching and lower dilution.

The impacts of changing CO2, temperature and rainfall will combine in different ways to affect groundwater recharge. Beare & Heaney (2002) examined the impacts of climate change on the hydrological cycle, using two scenarios that included a decrease in precipitation and an increase in evaporation over much of the Murray-Darling Basin. They found that under both climate scenarios the impact of climate change on recharge was a reduction in recharge and a general lowering of water table elevations. Woldeamlak et al. (2007), Brouyere et al. (2004) and Kuo-Chin Hsu et al. (2007) found that climate change led to decreases in rainfall and hence groundwater recharge, resulting in decreases in water table elevations. Ficklin et al. (2010) modelled groundwater recharge due to irrigation in semi-arid California, concluding that:

- Increased daily temperature led to increased evapotranspiration, resulting in an increased use of irrigation water that was potentially available for groundwater recharge;

- Increased atmospheric CO2 concentration increased crop water use efficiency, leading to decreased evapotranspiration rates and a reduction in the amount of water needed for irrigation; and
- Increased atmospheric CO2 concentration increased plant growth rates resulting in more irrigation needed earlier in the season.

Increases in groundwater pumping rates are expected by Woldeamlak et al. (2007) in response to lower rainfall and surface water availability. Recharge is also expected to be affected by increases CO_2 concentrations; Bouraoui et al. (1999, cited in Woldeamlak et al., 2000) reported a substantial reduction in groundwater recharge to an aquifer in Grenoble (France) under CO_2 doubling scenarios.

Changes in land use (e.g. crops) and land management (e.g. irrigation practices) resulting from climate change pressures will have indirect impacts on groundwater quality.

The implications of climate change on groundwater resources are likely to be delayed and subdued relative to the impacts on surface water resources. The most significant impacts of climate change on groundwater quality in the Murray-Darling Basin are the impacts on dryland salinity and river salinity.

5.5.3. Impact of Climate Change Induced Extreme Events on Water Quality

5.5.3.1. Impacts of drought on water quality

Extreme droughts can affect water quality either directly, indirectly or through the interaction of droughts with phenomena such as bushfires or erosion. Direct impacts are those that affect in-stream water quality, while indirect impacts are those that affect catchment characteristics (such as land management practices) and hence water quality. The interaction of drought with other events such as erosion, bushfires and dust storms, can also impact on water quality outcomes.

The impacts of drought on water quality parameters include:

- Temperature – high air temperatures during drought periods can directly increase water temperatures in streams and lakes, directly affecting biota and other water quality parameters;

- Dissolved oxygen – reduced flows, possible loss of hydrological connectivity and stagnation of flows, coupled with high temperatures can lead to decreased levels of dissolved oxygen;
- Salinity – droughts in the MDB can manifest in very high levels of salinity in streams or water holes, driven by reduced dilution and potential for saline groundwater intrusion and/or concentration, particularly in the southwest of the Basin in the lower ends of the Murray and Darling rivers;
- Pathogens – can increase due to increased stock access to waterways, and reduced flows. However, pathogen loads from diffuse catchment sources may be reduced with reduced catchment runoff;
- Nutrients – nutrients from diffuse sources may be reduced, however, ongoing loadings of nutrients from point sources such as water treatment plants combined with lower water volumes can have a concentrating effect;
- Algal blooms – elevated temperatures, low flows, and possible elevation of nutrients in surface waters can lead to an elevated risk of algal blooms. This subsequently increases the risk of adverse impacts of algal toxins on recreational users, drinking water users and stock; and
- Turbidity – turbidity may drop during drought periods where very little catchment runoff is observed. However, disconnected ponds of stagnant water are prone to high turbidity from bank erosion, possibly enhanced through hoofed stock access in particular.

There are a number of other chemical parameters expected to increase in concentration if doses to water bodies remain constant as volumes of water fall. These include pharmaceutical chemicals from wastewater treatment plants, chemicals from mining operations and potentially pesticides and fertilisers from ongoing agricultural use in catchments.

What is predicted for 2030 and where will be most affected?

Hennessey et al. (2008) predicted that the frequency and areal extent of exceptionally hot years and exceptionally dry years are likely to increase in the future. Their mean projections indicate that:

- for the period 2010 – 2040, exceptionally hot years are likely to affect about 65% of the MDB and occur every 1.6 years on average;

- for the period 2010 – 2040, little change is likely in the frequency and areal extent of exceptionally low rainfall years (considering the period between 1997 and 2006 has seen mean annual rainfall 16% lower than the long-term average across the MDB (Potter et al. 2010); and
- by 2030, exceptionally low soil moisture years are likely to affect about 7% of the MDB, and occur about once every 13 years on average.

The location and causes of water quality impacts due to extreme drought in the MDB will be variable and will depend upon: climatic drivers of future droughts (e.g. El Niño-Southern Oscillation (ENSO), Southern Annular Mode (SAM), Inter-decadal Pacific Oscillation (IPO)) and their subsequent impacts on rainfall variability and seasonality, the areas of the Basin affected and their hydrological response to rainfall deficits, and the value of water in the area.

5.5.3.2. Impacts of Heat Waves on Water Quality

As the future climate is expected to be hotter, it is anticipated that heat waves will become more intense, longer lasting and/or more frequent (Meehl &Tebaldi 2004). Heat waves in eastern Australia are usually associated with the ENSO, which brings a hotter and drier climate (Soh et al., 2008). Hun (2007), however, notes that ENSO is not exclusively linked to heat waves. An analysis of historical data by Deo et al. (2009) determined that the incidence of heat waves is increasing across eastern Australia, but generally decreasing in northern Australia.

The primary impact of heat waves on water quality is an increase in water temperatures. This is critical for aquatic environments, as temperature regulates many biotic and abiotic processes (Nelson and Palmer 2007). The coincidence of heat waves with lower rainfall and increased rates of evaporation can mean a severe reduction in river discharges and lake volumes. This in turn can lead to various impacts on aquatic biota and on water quality variables such as dissolved oxygen, pH, nutrients and contaminants, as well as affecting a number of biogeochemical processes (Meyer et al. 1999). Smaller water bodies are more susceptible to water temperature extremes, which may in turn exceed the thermal tolerance of some fish and macroinvertebrate species.

An increase in water temperature increases the rate of ecological processes in aquatic ecosystems, consuming more oxygen from the water column and lowering dissolved oxygen concentrations. Low levels of dissolved oxygen (<2 mg/L) are likely to cause fish mortality, while low dissolved oxygen levels more generally may cause the release of toxicants from sediments. This can lead to algal blooms and/or the contamination of the water column. Lastly, the saturation point for oxygen in water decreases as water temperature increases, meaning that warmer water bodies are physically unable to carry as much dissolved oxygen as cooler water columns.

The combination of heat waves and extended high temperatures due to climate change can result in prolonged thermal stratification of lakes and reservoirs. Reduced or non-existent water mixing can lead to low levels of dissolved oxygen in the lower layers of the water column, which reduces habitat and causes stress in aquatic organisms (Marce et al. 2010, Wilhelm and Adrian 2008). Nutrients (particularly phosphorus) can be released from bottom sediments under low dissolved oxygen conditions. Similarly, dramatic nutrient fluxes into the euphotic zone could occur after heat waves (Delpha et al., 2009). Algal blooms are supported by increases in nutrient levels and increased growth rates from higher temperatures (Paerl and Huisman 2008). Blooms of cyanobacteria can in turn shade non-buoyant phytoplankton, out-competing them for light (Paerl and Huisman 2008).

Whilst there is no clear evidence available, there are concerns that high water temperatures will lead to increased pathogen survival in the environment (Delpha et al. 2009).

5.5.3.3. Impact of Bushfires on Water Quality

Climate conditions since the 1950s have changed in ways that are likely to increase the frequency and intensity of bushfires (Hennessy et al. 2005; CSIRO 2007). Hennessy et al. (2005) modelled the impacts of climate change on fire-weather in south-east Australia and showed that the number of days rated as high to extreme on the McArthur Mark 5 Forest Fire Danger Index (FFDI) are likely to increase in number and occur over a longer fire season. Increased incidence of drought under climate change will increase the number of days when forest fuel is dry enough to burn, meaning that forest fire activity will increase under drought (Billing 2003).

Extensive bushfires impact catchment water quality, with increases in sediment, phosphorus and nitrogen loads in streams well documented (Brown 1972; Leitch et al. 1983; Atkinson 1984; Chessman 1986; Riggan et al. 1994; Lane et al. 2006). Large increases in sediment and nutrient loads have been observed immediately following bushfires, followed by a return to pre-fire loads over the following five years (Brown 1972; Leitch et al. 1983; Chessman 1986). Water yields from catchments also increase significantly for the first few years following bushfires, but drop to below pre-fire levels after about five years as forest re-growth consumes more water than the pre-burnt vegetation. Lane et al. (2009), in a study of East and West Kiewa Rivers in north-east Victoria, found that water quality recovery was a function of groundcover recovery.

5.5.3.4. Impacts of Floods on Water Quality

An emerging threat to water resources is the potential for an increase in extreme rainfall events, which may increase the risk of flooding through increased runoff (CSIRO 2006; Bates et al. 2008). Many global climate models (GCMs) indicate that future extreme rainfall is likely to be more intense, even in some areas where projections indicate a decrease in the mean seasonal or annual rainfall (CSIRO 2009). Extreme flood events, soil erosion, aquifer recharge and rising water tables may all result from increases in heavy rainfall (Fu et al. 2010).

The projected changes in rainfall intensity have been modelled on the projected increases in temperature (CSIRO 2006). For example, an increase in temperature of 1°C would result in a 10-20% increase in the intensity of extreme daily rainfall in NSW, but a 6% decrease in extreme daily rainfall in Victoria. However an increase in temperature of 5°C or more (in the longer term) may result in a 25% increase in extreme rainfall in Victoria (CSIRO 2006). In contrast, a key feature of the 'Big Dry' drought (1996-2009) has been a significant decline in rainfall intensity. With respect to changes in cyclone events, CSIRO (2006) referred to a study undertaken by McInnes et al. (2003) which projected a 5-10% increase in tropical cyclone wind speeds and a 20-30% increase in tropical cyclone rainfall if temperatures increased by 2-3°C. More recent analyses suggest a stable or declining frequency of cyclones, but a higher proportion of category 4 and 5 cyclones.

Heavy precipitation

The climate change modelling literature (CSIRO 2006; Dunlop and Brown 2008; Hennessy et al. 1997; Pittock 2003; Trenberth 1999) indicates that there is likely to be a trend of increasing intensity of extreme precipitation events in wet regions, extending through to regions that may be a little drier; however this may not be the case for regions becoming substantially drier as appears to be the case for the southern basin (Verdon & Kidd 2009; BOM 2010).

Increases in intensity of extreme precipitation events may translate to increased runoff and flooding. The implications of these events include increased flood severity, elevated erosion rates, potential for blackwater events (floodplain leaching) and increased challenges in water management (including water supply). Increases in precipitation intensity and the number of dry days across parts of the MDB will result in a new disturbance regime with water quality consequences not yet fully understood.

Tropical Cyclones

Abbs et al (2006) used CSIRO model simulations to assess changes in tropical cyclone frequency and intensity and noted that tropical cyclone frequency is forecast to decrease by 9% in 2070. However Abbs et al. (2006) project a significant increase in the severe category 3-5 (destructive) cyclones and an increase of 60% (2030) and 100% (2070) in the intensity of extreme tropical storms. The remnants of cyclones may indirectly impact on flooding in the northern MDB in the form of tropical low pressure systems and rain depressions. Limited research has been undertaken to assess whether there will be significant cyclone track changes under different climate change scenarios (Burton et al. 2007). Leslie et al. (2007, in CSIRO and Bureau of Meteorology 2007) observed a ‘change in the latitudinal extent of tropical cyclones, with more storms forming closer to the equator’ when researching projected changes in tropical cyclones in Australia.

Water Quality Impacts

According to Donnelly et al. (1998), storm events are the main precursors for major nutrient loadings of Australia’s rivers and storages. During an extreme rainfall event, runoff can readily transfer fertiliser to floodwaters, thereby elevating concentrations of nitrogen and phosphorus in floodwaters as opposed to river water. Generally, total suspended sediment concentrations are greatest during the first floods of a season, which are often referred to as the first flush (Wallace et al. 2009). High sediment concentrations in rivers typically result from inundation of floodplains where sediment has accumulated over time during relatively dry periods or has accumulated in dry watercourses (Wallace et al. 2009). Scott (2001) stated that investigations undertaken by Erskine and Sayner (1996) found that three catastrophic flood events of rivers in south-eastern Australia accounted for 11 to 283 times the mean annual sediment load from channel erosion alone. Brooker and Hennessy (2005) identify an increased likelihood of surface water contamination in areas with high densities of livestock after extreme rainfall events. Floodwaters also have the potential to transport faecal matter from sewers that overflow during floods, which can also lead to contamination of surface waters. Damage to sewage and water infrastructure can also occur in urban areas following heavy rainfall. More frequent flooding in summer, coupled with increased surface temperatures, might result in a significant increase in the frequency of mosquito-borne diseases like Ross River Virus. Contamination of river systems by chemical pesticides and insecticides can occur during flood events, particularly as the chemicals are often non-specific. Where a period of extensive drought has occurred and is followed by an extreme precipitation event, then the likelihood of contamination of a waterway may be increased through flooding. Dissolved oxygen can also be affected by floodwaters, particularly where a flood event results in the release of blackwater from the floodplain. Microbes require dissolved oxygen to process the carbon compounds found in blackwater and this often occurs at a rate that exceeds replacement, resulting in low levels of dissolved oxygen that is harmful to aquatic life (Baldwin and Whitworth 2009).

5.5.3.5. Impacts of Dust Storms on Water Quality

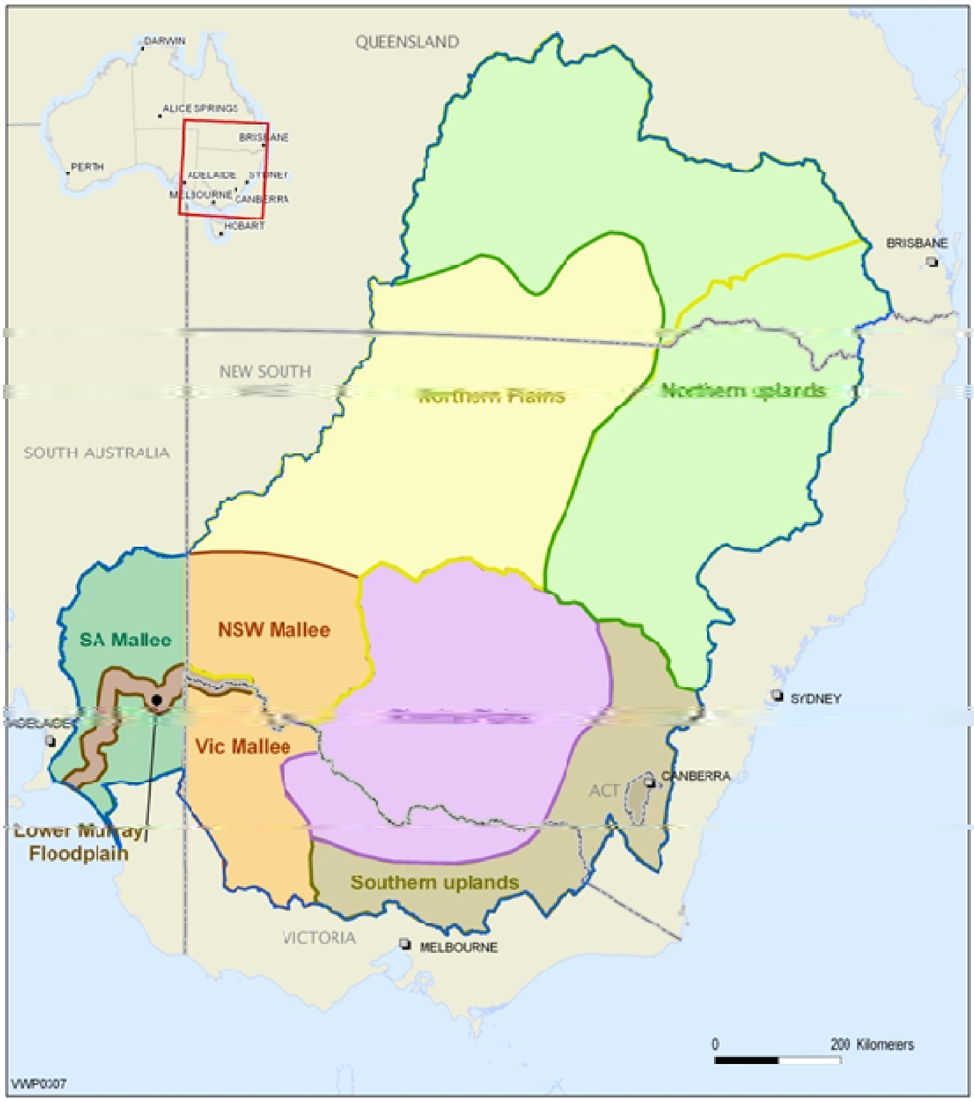
There is little information available with respect to direct water quality impacts of dust storms, primarily due to the lack of knowledge of the elemental and chemical nature of aeolian dust. Large areas of Australia experience frequent sand and dust storms and these storms are a feature of desert and arid soil zones globally. There is evidence that dust storms influence global processes of marine and freshwater nutrient flux and ecosystem processes such as seasonal oceanic algal blooms.

Aeolian dust transport also provides significant nutrients to catchments and rivers on a localised and catchment scale within arid zone environments and is important to micro and macro nutrient inputs and exports to MDB catchments in the arid zone (<400mm annual rainfall) (Bullard and McTainsh 2003). Riparian zone vegetation and tree cover contribute to catching transported dust particles, potentially an important form of catchment nutrient capture (Bullard and McTainsh 2003). During large dust storm events water quality has been affected with observed increases in suspended solids both during dust storms, and in first flush events following dust storms.

Cattle et al. (2005) found that by virtue of its major source in the Lake Eyre Basin, the salt composition of aeolian dust is considered to have had a major influence on salinity and erosion processes in the MDB. Cattle et al. (2009) found that smaller dust storm particles are susceptible to ‘rain out’ which would increase the salinity of rainfall and therefore soil and water courses, from general levels of dust suspended in the atmosphere. Increased salinity was found to occur in summer and spring months following the trend of the increased likelihood of dust storms in summer and spring (Hingston and Gailitilis 1976).

5.6. Climate change impacts on salinity dynamics and mobilisation processes

The assessment of climate change impacts on salinity in the MDB has been undertaken for five regions which represent broadly different salinity landscapes (**Error! Reference source not found.**). Each region is described in the following along with an assessment of potential climate change impacts on salinity.



- **Figure 5-1: Landscape Categories**

5.6.1. Methods

For this project, SKM took flow data from MSM and MSM-BIGMOD models that had been updated to reflect Sustainable Diversion Limits datasets. This data was then applied to the daily MSM-BIGMOD model, which provides predictions of river salinities. This model has recently been updated to reflect the CSIRO's C-Dry, C-Mid and C-Wet climate scenarios from the Sustainable Yields Project, which correspond to the dry, median and wet scenarios used for this project. These model runs formed the basis for salinity risks assessments in this project.

5.6.2. Northern Basin (Uplands and Plains)

5.6.2.1. Landscape Salinity Processes

The major source for salt in the Northern Basin is atmospheric salt from rainfall, and cyclic salt that is accumulated in the soil (Biggs, Power et al. 2005; Power, Johansen et al. 2005). In the upland alluvium, salinisation is associated with waterlogging in finer-grained sediments and poor irrigation practices. Land clearing across the granite system has led to shallow watertables and in some cases, salinisation.

In the Northern Basin, groundwater discharge and baseflow is generally not a significant contributor to river salinity due to relatively low groundwater levels. For Queensland, at least half of the identified dryland salt expressions occur in the Condamine catchment along the arc between Warwick and Bell (Power, Johansen et al. 2005). Many of these salt outbreaks emerged after the exceptionally wet period of the late 1940s/early 1950s, but have shrunk more recently due to the current prolonged drought (Searle, Watling et al. 2007). In the upper reaches of the Condamine-Balonne, salt is exported due to higher runoff and is being accumulated in the floodplains, a process which is being accelerated by river extractions for irrigation and stock watering (Power, Johansen et al. 2005). Salinity risks for the Warrego and Paroo to the west are low, due to low stream salinities, the extent of vegetation retention, low rainfall and high evaporation rates (Power, Johansen et al. 2005).

Salt outbreaks in the northern NSW uplands typically occur in low-lying areas with shallow watertables, break-of-slopes or where geophysical factors force groundwater to the surface. For the NSW Darling plains, local secondary salinity problems have emerged in the Bourke area and are largely associated with leakage from infrastructure (such as from off-stream storages) and rootzone drainage accessions. The impacts of salt mobilisation downstream of the Darling Plains are relatively limited due to:

- Significant channel losses (of both salt and water) occur through evaporation and groundwater accessions during overbank flows.
- The distance between salt sources in the uplands and its potential impact in the Lower Murray means that while relatively small rainfall events may create flows, these flows will be terminal.

5.6.2.2. Land and Water Use/Management Drivers

The hydrology of the Darling system is dominated by large scale episodic flooding events, with land and water management actions having a comparatively limited effect on the Darling’s impact on River Murray salinities. Increased vegetation clearing and land degradation from grazing in parts of the Northern Plains has increased erosion, surface runoff and scalding. Irrigation, evaporation and leaking from farm dams tend to further concentrate salts within the landscape (Power, Johansen et al. 2005; Searle, Watling et al. 2007).

There are concerns that watertables in irrigation areas are rising and may lead to salt exports in the future. For the Border Rivers and Moonie catchments, extensive clearing has occurred for grazing, however, the impacts on groundwater levels and discharge to streams have not yet been expressed. In the western catchments of Nebine, Mungalla, Warrego and Paroo, dryland salinity processes are localised and have not greatly impacted stream water quality.

5.6.2.3. Climate change impacts on river salinity

Austin et al. (2009) calculated the changes in salt load yields and the water yields in the MDB using the CSIRO's DAR125 and CC50 regional climate models. They found that under CC50, reductions in water yield and salt yield in the Northern Plains and Uplands averaged 25% and 15% respectively, putting the reduction in water yield within the range of the CSIRO scenarios. This means that on average, the combined effect of these two changes will be an increase in salinities by 10%. For impacts on the Northern Plains, any increase in salt loads or salinity will be significantly attenuated across the floodplains before reaching the Darling River (Power, Biggs et al. 2007). For the western catchments of the northern Basin, temperatures and evaporation are expected to rise such that runoff and deep drainage will decline, further reducing salinity risk (Power, Biggs et al. 2007).

The IPCC (2007) found a substantial upward trend in the severity of tropical cyclones since the mid-1970s, with a trend towards longer storm duration and greater storm intensity. This strongly correlates with the rise in tropical sea surface temperatures, with the IPCC concluding that a further increase in storm intensity is likely. Floods generated from tropical cyclones could increase, even under the dry climate scenario. Whilst cyclones rarely cross into the MDB, the northern Basin is influenced by tropical cyclone remnants, as well as tropical lows and troughs which contribute significantly to flooding. If cyclone intensity increases, it could exacerbate the salinity situation as far down as the main stem of the Murray – a major Darling flood could increase floodplain salt return to the lower River Murray, and this could coincide with low River Murray flows brought about by continuing dry climatic conditions. Historic flows at Burtundy and the Great Darling Anabranch, however, suggest that even with climate change the Darling might not be a frequent source of major flood inputs to the Murray.

Significant increases in salt loads to the lower Murray from the Darling River are therefore unlikely to arise under any future climatic scenario due to:

- Long distances from the catchments generating salts, and hence the necessity of very large flooding events in order for salts to reach the Murray River; and
- The extent to which salt is lost to the floodplain during large flooding events.

5.6.3. Riverine Plains

5.6.3.1. Landscape Salinity Processes

The hydrology of the Riverine Plain is heavily influenced by surface water diversions to irrigation channels and networks. Irrigation induced changes to the hydrology of the landscape are apparent throughout the region's irrigation areas, with shallow watertables and subsequent land salinisation problems appearing in the Kerang and Wakool Regions in the 1960s. In recent years, reduced winter/spring rainfall has led to declining groundwater levels within the Shepparton Irrigation Region, the Kerang region and the NSW Riverina. Within these areas, recharge is attributed to irrigation root-zone drainage 'or rainfall that has entered the groundwater system as a consequence of irrigation priming the unsaturated zone prior to rainfall events' (Cowan, Hunter et al. 2009).

The greatest salinity threat in the Riverine Plains is posed by irrigation areas, due to the additional drainage to surface water and aquifers. Watertable mounds contribute to water salinisation through the mobilisation of salt to the land surface through evapotranspiration, as well as through washoff and direct discharge to drains. The volume of surface drainage also has salinity impacts due to its dilution influence on downstream salinities (SKM 2009a).

As an example of dryland salinity in the Riverine Plains, the Tragowel Plains irrigation area is considered to be a surrogate for assessing a 'worst case' example. Prior to 1985, underlying groundwater salinity in the area was 50,000 EC and the watertable had been high since at least 1960. It is assumed that, given the retreat of watertables in the recent drought, the persistently high watertables that would generate ultimate salt load export rates would only occur in the wet climate scenario.

5.6.3.2. Land and Water Use/Management Drivers

A range of state and regional policies have driven salinity management, with the following drivers summarised from a range of sources (including REM 2008; NWC 2010; SKM 2010a). Water management initiatives stemming from the federal government's more recent role are also expected to have a profound impact on future salt mobilisation from the Riverine Plains. These policy drivers include:

- Reconfiguration of irrigation systems and on-farm irrigation;
- Buyback of irrigation entitlements;
- Water planning (e.g. the Basin Plan);
- Irrigator behavioural changes: the change from perennials to annuals and the accompanying restrictive management of water;
- Entitlement and allocation transfers: water trade has been actively encouraged over the last 15 years to reallocate "scarce water resources to higher value uses" so as to achieve

National Water Initiative Objective "of optimising the economic, social and environmental value of water" (NWC 2010).

5.6.3.3. Climate change impacts on river salinity

Climate change impacts will be determined by water availability, along with government policy and land management responses, such as the Basin Plan, trading trends and water use efficiencies. A drier regime is likely to lead to substantially reduced drainage flows and salt mobilisation emanating from the irrigated Riverine Plains, due to reduced allocations, water trade out of some areas, improved irrigation systems and on-farm irrigation efficiencies. Reductions in salt loads are particularly likely from the most saline sub-catchments across wet and dry scenarios as water trade is providing a financial mechanism that is encouraging water use on more productive land. A wetter regime is unlikely to significantly increase salt loads from those irrigation regions which historically contribute the highest salt loads to the Murray River, because:

- The rainfall and allocations under the wet scenario are not substantially higher than historical levels;
- In some areas, there is significant trade out through buyback or irrigator-to-irrigator transfers;
- Within Victoria, the water recovery initiative for the Living Murray has meant that annual allocations will not return to the levels provided for up until the mid 1990s;
- Improvements have occurred in on-farm irrigation efficiencies and reductions in system losses through modernisation.

This reduction in salt export is expected to have a significantly greater impact than the lessening of dilution that might also arise due to reduced drainage flows under the dry scenario. For the dryland plains, worst case scenario salt load estimates are relatively low, even under the wet scenario, and are hence unlikely to pose a significant risk under climate change. Finally, reductions in recharge due to climate change are likely to have subdued impacts on groundwater salinity, and therefore do not warrant close consideration (SKM 2010b).

As rising watertables are ultimately the cause of salt mobilisation, climate change will have the greatest impacts through changes in the distribution and intensity of irrigation. This will occur either directly, through changes in allocations, or indirectly, through policy or landholder initiatives that seek water savings. In recent years, reduced allocations have led many irrigators to change from perennial pastures to annual pastures due to their lower water use and to gain the flexibility to change crop types. Irrigation supply agencies have undertaken major irrigation distribution system reconfiguration/modernisation programs, which have in part been a state level water reform response to drier seasonal conditions (Ginnivan and Banting 2008). Reduced system losses arising from modernisation would be expected to reduce accessions to groundwater and hence reduce salt mobilisation. It is possible that reductions in return flows from surface drainage systems will increase long term average River Murray salinities. However, it is yet to be determined as to whether these impacts are entirely due to improved water use efficiency or also reflect the impacts of a shift in water use patterns (SKM 2009a).

5.6.4. Southern Uplands

5.6.4.1. Landscape salinity processes

Salt loads from the Goulburn, Loddon and Campaspe uplands are largely diverted to irrigation areas except during large flooding events. Groundwater salinity in the region is variable, with the fresher groundwater occurring in the higher-rainfall upper catchment areas that are less weathered and have lower salt stores. More saline groundwater, however, occurs in the foothills where deep weathering is prevalent and salt has accumulated from atmospheric salt via rainfall over thousands of years (URS 2008). One generalised characteristic is that within unregulated systems, higher salinities are concomitant with lower flows, and lower salinities with higher flows. Within the regulated systems, salinity variation is buffered by the storages, with variations in flow strongly dependent upon irrigation demand.

Dryland salinity occurs within the granites and acid volcanic rocks along the foot-slopes where the Uplands meet the colluviums of the Riverine Plains (URS 2008). Scalding occurs in salinised areas and saline seeps may develop where native vegetation has been cleared in these areas (SPPAC 1989; URS 2008). Extensive soil salinity has been associated with weathered granite in the Uplands (URS 2008), while a long history of clearing in the granites of the Central West Highlands has created salinisation across many parts of this landscape.

5.6.4.2. Land and Water Use/Management Drivers

Irrigation within the southern uplands tends to have natural relief and provide the drainage necessary to avoid the development of shallow watertables. Dryland salinity rather than irrigation salinity is therefore the major focus of catchment management prerogatives, which was largely driven by clearing up until the 1940s. Land and water management has primarily focused on re-vegetation of dryland pastures (i.e. with trees, native vegetation, groundwater irrigated crops, lucerne, etc.) that exhibit greater rooting depth and reduce recharge.

In recent years there has been increasing recognition that re-vegetation initiatives to combat salinity may be at the cost of reducing runoff, subsurface flow and hence stream flow. Research by Cheng et al. (2006) indicates that reductions to salt loads with minimal impact to stream flow can be obtained if tree planting is focused in areas of the landscape with relatively low water yield and high salt generation. Based on IPCC emissions scenarios, stream flow, baseflow and salt load will be reduced by at least 20% under current land use practices.

5.6.4.3. Climate change impacts on river salinity

Modelling by Austin et al. (2009) for the region found that the CC50 climate scenario gave reductions in water yield averaging 20% and salt yield averaging 12%, giving a combined effect of an increase in salinities by 8% on average. The predicted increases in salt load exports for the Lachlan are 2.8% and just 0.85% for the Murrumbidgee (DECC 2009), suggesting that the southern NSW upland catchments are unlikely to discharge significant amounts of additional salt under a wetter period than they did during the wet period that occurred during the latter part of the 20th century. Climate has not had a profound impact upon dryland salinity (Reid et al. 2008), possibly reflecting the importance of rainfall to provide leaching and wash-off to reclaim salt affected lands.

A significant portion of salt loads transported by regulated flows are diverted to the Riverine Plains, such that irrigation regions have become a sink for salt loads mobilised from the uplands. A wetter regime is therefore unlikely to lead to a substantial increase in salt mobilisation, while a drier scenario is likely to lead to reduced salt mobilisation. Historic diversions of upland salt loads may diminish if Riverine Plain irrigation regions contract, potentially leading to greater upland salt loads being carried into the Murray River during wet periods within the drier scenario.

5.6.5. Mallee

The Mallee region encompasses a range of landscape and land use types, with different salt mobilisation and salinity risks associated with these different sub-regions. As a consequence, salinity risks due to climate change in the Mallee region have been assessed individually for the dryland, irrigated, floodplain and Lower Lakes sub-regions of the Mallee.

Salt mobilisation to the River Murray in the Mallee region is a natural process as a result of saline inflows from highly saline regional groundwater. This ‘natural’ salinisation is aggravated by increased recharge in aquifers under irrigation districts, inflows of saline irrigation drainage water and river regulation downstream of Swan Hill. Increased regulation of the River Murray has provided for dilution flows for most of the time, such that the salinity hazard is very much event-based, although the water quality impacts can be prolonged over many months. However, river regulation has also led to a rise in groundwater levels such that floods are more likely to cause salt to be mobilised to the river system. Prior to regulation, salt mobilisation would have tended to be associated with low flow.

5.6.5.1. Dryland Mallee Landscape

Landscape salinity processes

In its natural state, the arid landscape was extensively vegetated with deep rooted Mallee vegetation. Large scale clearing for rain-fed agriculture changed the water balance, leading to increased recharge and hence increased salt loads to the River Murray (Barnett and Yan 2006). Salt mobilisation processes from these rain-fed landscapes are primarily driven by rootzone drainage, and are the consequence of historic land clearing actions that are likely to be realised over 100 years (SKM 2010a).

Land and Water Use/Management Drivers

Within the Mallee region, the emphasis has been towards minimising fallow and planting utilising deep rooted perennials. While programs have been targeted to reduce recharge, Cooke (2008) argues that in fact 'farmers modify their actions, practices and crops in response to market prices, technological change or social circumstances'. The range of uncertainties, and a lack of understanding of the rates of landscape change and its relationship with land management, means that any hypothesis on change has limited technical merit.

Climate change implications for river salinity

Dryland recharge rates from within the Mallee are relatively small, and as a result, shifts in the climate to either a drier or slightly wetter regime are unlikely to have a significant change in salt loads from the dryland. Uncertainties in existing rates of recharge are problematic, but these are unlikely to be as influential as other changes in the water system.

5.6.5.2. Irrigated Mallee landscape

Landscape salinity processes

Salinity impacts of irrigation are primarily driven by irrigation rootzone drainage, the volume of water that moves beyond the plant rootzone (Newman, Currie et al. 2009). Rootzone drainage recharging the groundwater system displaces additional regional saline groundwater to the river and surrounding floodplain. Rootzone drainage is therefore a critical salt mobilisation factor in terms of increasing regional groundwater gradients to the river.

Land and Water Use/Management Drivers

In the irrigated parts of the Mallee, drainage systems have commonly been implemented to divert subsurface drainage flows inland and away from the river. Improvements to irrigation practices over the past few decades have resulted in reduced subsurface drainage flows and reduced root zone drainage, and hence reduced irrigation accessions to groundwater (SKM 2010a). However, irrigation applications above crop evaporative requirements remain essential to leach accumulating salts (Newman et al. 2009). It should be noted that there time lags of 25-50 years between the commencement of irrigation in region and the observation of salinity impacts, such as seepage onto the floodplain and changes to river salinities (URS et al. 2005).

Climate change implications for river salinity

The impacts of climate change on irrigation development may be an important driver of future salinity outcomes. Connor et al. (2008) undertook an analysis of the likely changes in the irrigation footprint in the Mallee region and concluded that:

- The water demand and irrigation footprint would remain essentially the same as now;
- Irrigators would become more efficient; and
- Salt mobilisation from irrigation would be relatively unchanged, however, salt would be mobilised into a river with reduced flow and would therefore have a greater salinity impact.

SKM (2010a) observed that the recent drought heavily impacted irrigation in the region, noting that:

- This was clearly an issue during the recent drought, when annual allocations in South Australia fell by 50% or more and the irrigation footprint fell by around 15% (PIRSA 2010). In other words, the drought had a profound impact upon the viability of irrigated horticulture;
- It is uncertain as to whether the contraction PIRSA (2010) observed in the irrigation footprint represents long-term retractions that will arise from reduced allocation at a time of low commodity prices, or whether it is more a short-term structural adjustment that impacted upon less efficient operations; and
- Increasing water scarcity and associated increased value of water may lead to increasing water use efficiencies which would reduce rootzone drainage and hence groundwater displacement to the river.

5.6.5.3. Mallee floodplain

Landscape salinity processes

Regional groundwater flow systems feed groundwater both directly to the river and to the floodplain, where evapotranspiration processes lead to salt accumulation in the unsaturated zone. Salinity monitoring data following flood events illustrates a fall in river salinity during the flood event, due to large volumes of water providing dilution, but dramatic rise in-river salinity levels upon flood recession. The key floodplain processes can be broadly explained as floodwaters carrying salt to the river either through overland flow, or through interflow and groundwater discharge. This flood surcharge continues to be released to the river over periods of up to 12 months or more after major flood events.

Land and Water Use/Management Drivers

River levels have been maintained at artificially high levels for long periods of time due to river regulation, thus affecting the ability of the groundwater system to discharge back to the river during low flow events. The movement of water between surface and groundwater systems is also affected by the manipulation of locks for operational or maintenance purposes. Finally, salt accessions to the River Murray may be driven by the environmental watering of saline wetlands (such as the Chowilla Floodplain).

Climate change implications for river salinity

The historical salinity records for low flow periods following high flow events demonstrate that such sequence of events pose significant risks to water quality (SKM 2010a). The implications of reductions in the frequency of larger floods are that there will be reduced salt mobilisation in the lower Murray. However, a reduced threat of salt mobilisation under dry climatic conditions is countered by the likelihood of increased incidents of shortfalls in South Australian entitlement flows. This would in turn have a detrimental impact on floodplain ecological assets, with reduced flushing of accumulating salts.

5.6.5.4. Lower Lakes

Landscape salinity processes

The principal landscape drivers of salinity outcomes for the Lower Lakes are evaporative losses estimated to be around 800 GL/annum (Andy Close, MDBA, pers. comm.). Other causal factors include flows to and through the lakes and the operation of the barrages (SKM 2010a). With no input from external sources, the water in the Lakes has slowly evaporated and was progressively salinising, with water levels only now rising again. The extent of this salinisation has meant that in recent years there has been no irrigation water sourced from Lake Albert (PIRSA 2010) and Lake Alexandrina (Phil Cole, MDBA, pers. comm.).

Land and Water Use/Management Drivers

The lack of inflows to the lakes that is the cause of the lack of salt exports could be at least partially addressed, even in dry phases, by providing greater allocations to the lakes. The main land and water management intervention that has been implemented to protect the lakes in recent years has been to maintain closure of the barrages separating the Lakes from the sea to prevent oceanic inundation (SKM 2010a).

Climate change implications for river salinity

Climate change impacts on the lower lakes are likely to be fairly well typified by the decline in discharge to sea and the consequential salinisation problems that have emerged to date. The extent to which a future dry climate scenario leads to a repeat of the recent problems for the lower lakes will be dependent upon how the needs of the Lower Lakes are incorporated into management decisions, such as the Basin Plan.

5.7. Impacts of Climate on the Aquatic Ecosystems of the MDB

5.7.1. Introduction

The challenge for ecologists is to predict the responses of species and communities to human-induced climate change over and above the background natural ecological variability. The biological consequences are further confounded by impacts on ecosystems of other human activities, such as land-use change and water resource development.

This report reviews three climate change drivers for inland aquatic ecosystems: **increasing temperature** (air and water), **changing patterns of precipitation** (rainfall and runoff), and **increased UVB-radiation** (which may have significant impacts on resting stages in high irradiance floodplain environments).

5.7.2. Potential climate change impacts on aquatic ecosystems

Climate change will have many complex impacts on aquatic ecosystems. The types of affects are listed below:

- physiology, distribution, phenology and, in some cases, evolutionary adaptation of species globally
- animal and plant interspecific interactions; competitive balances will be altered and changes in competition may alter ecosystem structure
- altered ecosystem hydrology and thermal regimes and given that many freshwater organisms have precise thermal and hydrological tolerances place them under increasing threat
- increased global temperatures and regional changes in precipitation, evaporation and runoff, make some areas wetter and others drier; this will redistribute freshwater systems but dispersal capacity and geographical and human barriers will limit colonisation of new locations
- increases in water temperature and evaporation and changes in precipitation will influence the flow regime of inland systems which in turn will influence channel form and water chemistry.

Habitat availability and water chemistry changes will impact on species distributions and abundance as well as ecosystem processes

- Changes in precipitation, temperature and evaporation will influence the stratification of many inland water bodies, with increased periods of high water temperature potentially leading to stronger and more sustained periods of water body stratification. This will have impacts on water chemistry and the productivity of water bodies, which in turn will impact species diversity and abundance and ecosystem processes
- the increased disturbance pressure of climate change on many aquatic ecosystems, over and above other anthropogenic impacts, will result in biodiversity loss
- Thomas *et al.* (2004) predict that 15-37% of species of a wide variety of taxa (of a sample of 20% of the terrestrial surface) will be 'committed to extinction' by human-induced climate change
- an increase in UVB-radiation has potential unknown impacts, particularly in places of high irradiance, such as floodplains of inland rivers
- aquatic ecosystems are sensitive to temperature due to the high heat capacity of water
- Changes in land use and climate and biotic additions and losses in ecosystems interact to result in biodiversity loss
- Climate change, with the associated changes in land use, atmospheric CO2 concentration, nitrogen deposition and acid rain, and introductions of exotic species, is considered one of the most important influencing factors in the currently observed changes of global biodiversity; it is predicted that rivers with reduced discharge as a result of climate change and increased human water consumption may lose up to 75% of their fish species by 2070

5.7.3. The climate change temperature driver

Temperature is probably the most important environmental variable for freshwater biota, affecting metabolic rates, development. Abiotic changes due to temperature increases will in turn affect a wide range of aquatic and freshwater-dependent organisms. Species' distributions, both latitudinal and altitudinal, may change due to alterations in availability of habitat, both physical and thermal. This may result in fragmentation of populations.

There will be additional changes to phenology, spawning, recruitment, metabolism, growth, productivity, population dynamics, sex ratios, sexual vs asexual reproduction, predator-prey interactions, host-parasite relationships, bacterial activity and contamination, and bioaccumulation of toxins (see Table 4). This will affect mortality rates of many species and, with additional factors such as increased likelihood of invasion, will alter community structure due to loss of local diversity and extinctions.

Another important way by which temperature may exact unpredictable changes on aquatic and terrestrial ecosystems is via extreme events, such as heatwaves and increased frequency and severity of bushfires. While bushfire risks have received the most attention, the direct effect of heatwaves may also be severe. For example there is a clearly established increase in rates of mortality in human populations during heatwaves, and anecdotal evidence suggests that a recent heatwave several weeks prior to the bushfires in Victoria in January 2009 caused numerous fish kills following 4 days of temperatures above 40oC and high overnight minimum temperatures. These effects will be most pronounced in smaller waterbodies due to their lower thermal capacity and hence increased rate of warming.

These changes due to temperature increase will be species-specific and will vary with season, region, and between and within habitats. For example, impacts within streams will vary strongly with channel morphology and hydrology and with location, i.e., north- or south-facing. The effects of temperature will be also compounded by synergistic interactions with other factors such as nutrients or streamflow.

■ **Table 5-2: Biotic consequences of increased temperature on freshwater ecosystems**

Change (to)	Organism(s)	References
Available thermal habitat	1 fish 2 macroinvertebrates	Coutant 1990 1; Hill and Magnuson 1990 1; Johnson and Evans 1990 1; Magnuson *et al.* 1990 1; Meisner 1990; Henderson *et al.* 1992 1; DeStasio *et al.* 1996 1; Magnuson *et al.* 1997; Eaton and Scheller 1996 1; Hauer *et al.* 1997 2; King *et al.* 1999; Clark *et al.* 2001 1; Daufresne *et al.* 2003 1, 2; Dunham *et al.* 2003 1; Hastie *et al.* 2003 2; Jansen and Hesslein 2004 1; Dobiesz *et al.* 2005 1
Distribution (latitudinal)	1 zooplankton 2 fish 3 macroinvertebrates	Coutant 1990 2; Johnson and Evans 1990 2; Chen and Folt 1996 1; DeStasio *et al.* 1996 1; Eaton and Scheller 1996 2; Daufresne *et al.* 2004 2; Hickling *et al.* 2005 3; Hickling *et al.* 2006 2, 3
Distribution (altitudinal)	1 fish 2 macroinvertebrates	DeStasio *et al.* 1996 1; Hauer *et al.* 1997 2; Clark *et al.* 2001 1; Hickling *et al.* 2006 1, 2
Population connectance	1 macrophytes	Rahel *et al.* 1996; Brinson and Malvárez 2002 1
Available habitat (DOC)	1 fish	Blumberg and Di Toro 1990 1
Phenology	1 amphibians 2 phytoplankton 3 zooplankton 4 reptiles 5 fish 6 algae 7 macroinvertebrates	Coutant 1990 5; Beebee 1995 1; Chen and Folt 1996 3; Hogg and Williams 1996 7; Jager *et al.* 1999 5; Blaustein *et al.* 2001 1; Clark *et al.* 2001 5; Gibbs and Breisch 2001 1; Gerten and Adrian 2002 3; Jansen and Hesslein 2004 5; Bowen *et al.* 2005 4; Hampton 2005 6; Adrian *et al.* 2006 2, 3; Elliott *et al.* 2006 2
Species coupling	1 fish/mollusc	Hastie *et al.* 2003 1
Spawning (other than timing)	1 fish	Beacham and Murray 1990 1; Coutant 1990 1; Henderson *et al.* 1992; Jager *et al.* 1999 1; Clark *et al.* 2001 1; Gibson *et al.* 2005 1
Recruitment	1 fish 2 macroinvertebrates	Daufresne *et al.* 2004 1; Hastie *et al.* 2003 2; Borgstrøm and Museth 2005 1
Metabolism and growth	1 fish 2 macroinvertebrates	Coutant 1990 1; Hill and Magnuson 1990 1; Henderson *et al.* 1992 1; Hogg and Williams 1996 2; King *et al.* 1999 1; Jonsson *et al.* 2005 1
Productivity	1 picoplankton	Christoffersen *et al.* 2006 1
Mortality	1 zooplankton 2 fish	Johnson and Evans 1990 2; Chen and Folt 1996 1; Daufresne *et al.* 2004 2
Population dynamics	1 phytoplankton 2 zooplankton 3 fish 4 macroinvertebrates	Hogg and Williams 1996 4; Magnuson *et al.* 1997 1, 2; Adrian *et al.* 1999 1, 2; Baines *et al.* 2000; George 2000 2; Clark *et al.* 2001 3; Anneville *et al.* 2002 1; Gerten and Adrian 2002 2; Daufresne *et al.* 2004 3; Hampton 2005 1, 2; Holzapfel and Vinebrook 2005 2; Elliott *et al.* 2006 1; Markensten 2006
Sex ratios	1 macroinvertebrates 2 reptiles	Janzen 1994a 1; Hogg and Williams 1996 1
Sexual/asexual reproduction	1 zooplankton	Chen and Folt 1996 1
Predator-prey interaction	1 fish/macroinvertebrate 2 fish/zooplankton	Henderson *et al.* 1992 2; DeStasio *et al.* 1996 2; Daufresne *et al.* 2004 1; Jansen and Hesslein 2004 1
Invasion potential	1 zooplankton 2 fish	Mandrak 1989 2; Johnson and Evans 1990 2; Magnuson *et al.* 1997; Dukes and Mooney 1999 2; Hampton 2005 1; Holzapfel and Vinebrooke 2005 1
Species richness	1 fish	Chu *et al.* 2003 1
Species loss and extinction	1 fish	Covich *et al.* 1997 1; Gibson *et al.* 2005 1
Community structure	1 zooplankton 2 fish 3 macroinvertebrates 4 phytoplankton	Henderson *et al.* 1992 1, 4; Chen and Folt 1996 1; Daufresne *et al.* 2004 2, 3; Anneville *et al.* 2005 4
Bacterial activity and contamination		Blumberg and Di Toro 1990; Caruso 2002
Bioaccumulation of toxins		Moore *et al.* 1997

5.7.4. The climate change precipitation driver

Climate change is expected to result in a more intense hydrological cycle due to increases in evaporation and changes in the distribution of precipitation. Although changes in precipitation are difficult to generalise, even at very large scales, during the 20th century regional precipitation patterns changed, with increases of between 2 and 12% in some regions, and marked decreases in others. There has been a 2 to 4% increase in the frequency of heavy precipitation events over most of the Northern Hemisphere and an increase in frequency and intensity of droughts in parts of Asia and Africa. Heavy precipitation has increased even within some regions where mean total precipitation has decreased, suggesting an increase in rainfall variability.

Changes in precipitation will affect freshwater ecosystems through changes to the quantity and timing of runoff, streamflow volume and variability, frequency and magnitude of floods, water levels, groundwater recharge, snow accumulation, hydrochemistry, sediment loads and turbidity, input of coarse woody debris, channel morphology, and frequency and magnitude of streambed scouring.

The above effects will vary both between and within ecosystems. Increased precipitation may also be offset by increased evapotranspiration due to increased temperatures and it is necessary to consider precipitation and potential evapotranspiration simultaneously, especially where precipitation and evaporation are nearly balanced. Other components of climate change, such as changes in wind speed, will also influence rates of evapotranspiration.

Reduced precipitation and/or increased variability may affect freshwater ecosystems by encouraging colonisation by emergent plants, transforming shallow lakes into marshes, reducing habitat for aquatic and wetland-dependent organisms, reducing food resources, altering the phenology of fauna and flora, reducing recruitment, reducing biodiversity, increasing plant invasion potential, changing community structure and altering food webs, shifting species distributions within streams, and reducing instream and riparian production (see Table 5). Any reduction in precipitation will have the greatest impact in arid regions and the effects of prolonged dry periods may not be limited to the season or year of occurrence due to changes in surface and groundwater levels.

Table 5-3 Biotic consequences of reduction in precipitation and/or seasonal shift in runoff on freshwater ecosystems

Change (to)	Organism(s)	References
Colonisation by macrophytes		Lafleur 1993; Labaugh *et al.* 1996; Singer *et al.* 1996
Likelihood of fire	1 macrophytes	Smith *et al.* 2003 1
Water stress	1 macrophytes	Dawson *et al.* 2003 1
Food resources		
Phenology	1 reptile 2 amphibian	Corn 2003 2; Bowen *et al.* 2005 1
Spawning	1 fish	Jager *et al.* 1999 1
Recruitment	1 fish 2 mollusc 3 reptile 4 bird	Poff *et al.* 1997 1; Sorenson *et al.* 1998 4; Hastie *et al.* 2003 2; Borgstrøm and Museth 2005 1; Madsen *et al.* 2006 3
Loss of breeding habitat	1 bird 2 fish	Larson 1994 1; Bethke and Nudds 1995 1; Gibson *et al.* 2005 2; Kingsford and Norman 2002 1
Loss of non-breeding habitat	1 mollusc 2 fish 3 bird	Gibson *et al.* 2005 2; Kingsford and Norman 2002 3; Hastie *et al.* 2003 1; Sorenson *et al.* 1998 3; Smith *et al.* 2003 3
Biodiversity	1 macroinvertebrates 2 fish	Woodward *et al.* 2002; Xenopoulos *et al.* 2005 2
Invasion potential	1 macrophytes	Poff *et al.* 1997 1; Wei and Chow-Fraser 2006 1
Community structure	1 fish 2 macroinvertebrates	Poff and Allan 1995 1; Woodward *et al.* 2002 2; Lake *et al.* 2000 2; Gibson *et al.* 2005 2
Food web structure		Poff *et al.* 1997; Lake *et al.* 2000
Productivity		Grimm *et al.* 1997
Distribution (within stream)	1 macroinvertebrates 2 fish	Clinton *et al.* 1996 1; Schlosser *et al.* 2000 2
Bacterial contamination		Caruso 2002

5.7.5. The UV-B Radiation driver

The stratospheric ozone layer has been depleted by anthropogenic emissions of chlorofluorocarbons and other substances, leading to increased ground-level flux of UV-B radiation. International efforts have arrested these emissions and the abundance of ozone-depleting gases in the atmosphere is expected to continue to decline, having peaked in the 1990s. The expected reversal, however, has yet to materialise and research continues into the impacts of UV-B radiation on aquatic biota.

The influence of clouds, altitude, solar zenith angle and surface albedo on surface UV radiation levels make it difficult to identify the importance of anthropogenic emissions. Climate change is likely to reduce ice cover, which strongly attenuates UV radiation.

UV-B radiation is potentially damaging to a wide variety of aquatic organisms and high levels may result in changes to both lentic and lotic community structure. It produces genetic, cytotoxic and photochemical effects, affects photosynthetic rates and productivity and may influence many trophic levels simultaneously. Increased fluxes of UV-B radiation may affect the population dynamics of algae phytoplankton, macroinvertebrates, and fish.
UV-B radiation may also have synergistic interactions which produce detrimental effects. For example, interactions with a pathogen have been shown to kill amphibian embryos and irradiated pesticide by-products create toxic substances in wetlands. Dissolved organic carbon concentration inhibits UV-B radiation penetration but exposure of DOC has multiple effects that both increase and inhibit bacterial production.

Although the absorption of UV-B radiation by water will protect many aquatic organisms, communities in shallow, clear-water lakes and ponds may still undergo substantial changes. In addition to the impact of reduced ice cover, the effects of UV-B radiation will be exacerbated by fluctuations in DOC concentrations as a result of processes in the catchment, by increased wind speeds, which result in shallow water bodies being well mixed, and by the loss of riparian vegetation.

5.7.6. Impacts on Murray-Darling Basin biota

5.7.6.1. Climate Change impacts on fish

Amongst the fish of the Murray-Darling Basin, some are predicted to increase their range and abundance under climate change scenarios while others will be disadvantaged.

Murray cod (*Maccullochella peeli peeli*)

Increases in ambient temperatures through summer will be likely to result in an increase in the prevalence of fish kills involving cod due to their sensitivity to temperature stress. Such events are likely to arise when there are multiple consecutive days of high temperatures (e.g over 35^0C). Decreased precipitation could lead to fewer refugia due to less water in the system and potentially lower productivity with reduced flows could also have flow on effects for fish productivity. Furthermore, less flow would reduce biological connectivity among habitats, river reaches and waterholes leading to lower genetic fitness given the high panmixia of the cod populations.

Yellowbelly (*Macquaria ambiguai*)

In the Northern MDB, higher temperatures could actually lead to increases in abundance of temperature tolerant fish such as yellowbelly. The closely related Lake Eyre Yellowbelly thrives in shallow floodplain waters that regularly exceed 42^0C suggesting that MDB yellowbelly could also flourish in highly productive warm waters. Being ecological generalists more dry spells and perhaps fewer flows may change the temporal dynamics of this species, however, their ability to spawn regularly and quickly in response to favourable conditions (booms of productivity) means they are less likely to be affected by changes to hydrology, compared to the effects of flow regulation. In the southern MDB increases in temperature could also enhance the productivity of these fish with more spawning events, higher recruitment and probably increased primary and secondary productivity.

Eel tailed catfish (*Tandanus tandanus*)

Reduction in flow volume may impact on this species throughout their range; however associated increase in temperature may advantage them, particularly in the Southern MDB. This temperature increase may offset some of the effects of coldwater pollution.

Hyrtl's tandan (*Neosilurus hyrtlii*)

Temperature increase may advantage these fish and they would be likely to extend their range. Changes to hydrology may also advantage them in some instances as they can be prolific in highly variable systems, particularly when flow events do occur. This could happen in a drier climate with larger but less regular floods.

Bony bream (*Nematolosa erebi*)

Although bony bream are susceptible to handling stress and potentially low DO, they have still been found in high numbers in isolated waterholes subject to extreme temperatures in Cooper Creek. Hence increased temperature is not likely to have a drastic effect on them. They may also increase their range under increased temperatures, especially if higher primary productivity results. Altered hydrology, such as more frequent high flows or reduced annual flow volume are also unlikely to affect this generalist species.

Carp gudgeons (*Hypseleotris* spp.)

Carp gudgeons are highly tolerant of poor water quality and as such can tolerate extremes of temperature and low DO. Hence any impacts of climate change that results in an overall increase in water temperature may actually advantage these fish particularly if more temperature sensitive species are reduced. Flow impacts are also likely to be minimal on carp gudgeons as they are ecological generalists and can be found in both stable water conditions such as highly disconnected billabongs and in main channels.

Flathead gudgeon (*Philypnodon grandiceps*)

It is unknown whether changes to precipitation and flow regimes and their corresponding effect on inundation rates and/or levels of floodplain wetlands, will affect flathead gudgeons. Although flathead gudeons have a high temperature tolerance, it is unknown whether increased wetland temperatures and the subsequent follow-on-effect on foodweb stability and habitat structure within the wetland will affect populations. Warming temperatures may also lead to earlier spawning which may eventuate in juvenile mortality if food is not available. Reduced precipitation rates will decrease flow to the estuary, which may cause the estuary to be temporarily or periodically blocked. Intermittently closed estuaries are often associated with fish kills which will reduce gudgeon populations. Increased salinity levels from salinisation will affect macroinvertebrates (the primary food source of flathead gudgeons) and macrophyte structure (gudgeon habitat). However, with stablising base flows in the lower MDB macrophyte habitat availability will be more prolific.

Hardyhead (*Craterocephalus stercusmuscarum fulvus*)

It is unknown whether increased wetland temperatures will destabilise hardyhead foodwebs and threaten habitat structure within wetland populations. Warming temperatures may lead to earlier and longer spawning season, which will lead to juvenile mortality if food is not available. Adult mortality rates may also increase if water temperatures exceed their tolerance range. Increases in salinity levels from salinisation will have a negative effect on macroinvertebrates (main food source). There will also be an increase in competition from introduced species which is expected to be detrimental to hardyhead populations, e.g. eastern gambusia, which are expected to thrive from climate change impacts. There will be, however, an increase in macrophyte habitat availability in the lower MDB, which will be advantageous for southern lowland populations. The current effect of coldwater pollution on hardyheads may be decreased with warming water temperatures.

Australian smelt (*Retropinna semoni*)

Increased salinity levels from terrestrial influx will be damaging on macroinvertebrate populations, the primary food source of smelt. Warming temperatures may lead to earlier spawning which, if food availability is diminished from salinity levels, will lead to juvenile mortality. Populations may also be lost from unregulated tributaries where increased flow intermittency may lead to increased levels of habitat loss and fragmentation.

Macquarie perch (*Macquaria australasica*)

With warming temperatures, the effect of coldwater pollution may be less damaging on populations. On the other hand, warming temperatures may increase redfin perch (*Perca fluviatilis*) populations which carry the Epizootic Haematopoietic Necrosis Virus, therefore increasing exposure of Macquarie perch to the virus. Warming temperatures may induce earlier spawning which will lead to juvenile mortality if food is not available. Habitat modification from increased sedimentation from climate change impacts on terrestrial vegetation is also expected to impact on perch.

Southern pygmy perch (*Nannoperca australis*)

If climate change favours introduced species (redfin perch and eastern gambusia), predation on and competition with *Nannoperca australis* will increase. With warming water temperatures, the effect of coldwater pollution may be less damaging on populations. However, warming temperatures may lead to earlier spawning which may result in juvenile mortality if food is not available. Increased water temperatures may also exceed the temperature tolerance range of southern pygmy perch leading to species mortality.

Trout cod (*Maccullochella macquariensis*)

With warming water temperatures, the effect of coldwater pollution may be less damaging on populations. Warming temperatures may be detrimental as it may induce earlier spawning leading to juvenile mortality if food is not available. Increased water temperatures may also exceed their tolerance range, leading to adult mortality. Competition will increase with introduced species thriving on climatic changes (redfin perch and trout). As well as these impacts, habitat modification from reduced riparian zone (desnagging and loss of riparian vegetation) and sedimentation will be detrimental to trout cod populations.

Two-spined blackfish (*Gadopsis bispinosus*)

Increases in temperature and streamflow will decrease the range of this species by causing altitudinal contractions. Increased sedimentation associated with low flows may also cause local impacts where streamflows are reduced as eggs are particularly susceptible to sedimentation. Warming temperatures will induce spawning/hatching earlier which may be detrimental to juveniles if aquatic insect larvae (main food source) are not available. Competition and predation by trout (introduced species) will increase as climatic change to the region will favour such species. Increased temperature will cause an increase in fungal infection which becomes a problem when temperatures exceed 22-24oC. Preference to cool streams will also restrict the range of the species and as two-spined blackfish are usually territorial and aggressive toward other individuals, aggression may increase if range is restricted due to both temperature or water quality. Increased water temperatures may also exceed the maximum tolerance range which would lead to mortality. Populations incurring coldwater pollution may be advantageous by warming waters.

River blackfish (*Gadopsis marmoratus*)

Climatic related loss of riparian vegetation will reduce available habitats (e.g. loss of snags, loss of undercuts). This will largely influence eggs as increased sediment loads will cover eggs and spawning sites as well as desnagging will reduce suitable adhesive sites for eggs. Replacement of deforested native riparian species with introduced species such as weeping willow trees (*Salix babylonica*), will not always provide suitable habitats (ie willow logs do not hollow). Competition with introduced species (redfin and trout) and predation by introduced species that have undergone climate change induced population booms will have a negative effect on blackfish populations. Warming temperatures may lead to earlier spawning which will lead to juvenile mortality if food is not available. Increased water temperatures may also exceed the species temperature tolerance range which will lead to mortality. Populations incurring coldwater pollution may be advantaged by warming waters.

5.7.6.2. Climate Change impacts on riparian and floodplain vegetation

River red gum (*Eucalyptus camaldulensis*)

Climate change impacts on river red gum are most likely to manifest themselves through changes in the frequency and magnitude of floodplain inundation events. In areas where trees and forests are already stressed by water resource development, the increased stress associated with further reductions in flooding may be enough to cause mass death of red gums. Increased duration of dry spells along with higher temperatures may also reduce survivorship amongst recruiting seedlings.

Black box (*Eucalyptus largiflorens*)

Climate change, as depicted by the current scenarios, is unlikely to have major impacts on black box woodland. In fact a decrease in the frequency and duration of flooding across floodplains in the MDB, combined within higher air temperatures, may well allow an increase in the range of black box, being already well adapted to higher air temperatures and reduced flooding.

Lignum (*Muehlenbeckia florulenta*)

Again like black box, climate change, as depicted by the current scenarios, is unlikely to have major impacts on lignum stands. In some of the less frequently flooded regions of the MDB, higher air temperatures combined with reduced rainfall may cause declines in the health and habitat value of existing lignum stands.

Grasslands

Further reductions in flooding duration and frequency will have a major impact on Moira grass plains. Higher air temperatures combined with lower humidity have the potential to threaten germination of seeds through reduced soil moisture.

Further reductions in flooding duration and frequency are likely to impact water couch stands.

Further reductions in flooding frequency may have an impact on Phragmites (common reed) in terminal floodplains, especially when combined with higher air temperatures and lower humidity, which may impact the survival of rhizomes within the sediment.

Rushes, Sedges and Cumbungi

Climate change impacts that reduce the frequency and extent of floodplain inundation in the southern parts of the MDB are likely to impact the distribution of rush plants. The impact of higher air temperatures and reduced humidity on the rhizomes of sedges in the drier parts of the basin is unknown. *Typha* stands may well be extended in certain regions of the MDB under climate change scenarios as warm, nutrient conditions see it attain maximum growth. Where water levels and soil moisture are reduced and the periods between flooding extended, *Typha* stands will disappear.

5.7.6.3. Climate Change impacts on other faunal groups

Zooplankton

The diversity of zooplankton assemblages, and their ability to respond to flooding, will be influenced by:

- changes in the frequency and duration of floodplain inundation, which may reflect changed patterns of precipitation;
- changes in the chemical properties of water inundating the floodplain;
- higher air temperatures during the non flood period, which may exceed the thermal tolerance of desiccation resistant stages; and
- increased UVB radiation may impact desiccation resistant stages and reduce the response when floodplains do become inundated.

Freshwater Mussels

In the northern regions of the MDB, reduced periods of flow and increased periods of waterhole isolation may provide a thermal risk for the large river mussel.

A review of the global literature on the impacts of climate change on biota is provided in Appendix F. The review covers freshwater fish, riparian vegetation, aquatic and emergent plants, and waterbirds.

6. Overview of MDBA Climate Change NRM Impacts Knowledge

6.1. Introduction

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 section attempts to summarise the current state of knowledge of climate change in the Murray-Darling Basin (MDB). In doing so, the paper draws on the substantial body of international and national research and recent projects and science reviews funded by the Murray-Darling Basin Authority (MDBA).

6.2. Definition of climate change

It is important for any discussion of climate change to be clear on definitions, scope and perspective. The Inter-governmental Panel on Climate Change (IPCC) (2007a: 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 etc.) causing impacts (bushfires, floods etc.). This approach recognises ‘feedbacks’ from impacts to ‘causes’ that may 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 economic, policy and social issues.

6.3. Science of climate change

The science of climate change has recently been well summarised by the Royal Society (2010). 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; has wide consensus but still debated; and topics not well understood. The latter aspects relevant to the MDB are:

- 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 the climate sensitivity;
- 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 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;
- The future strength of the uptake of CO_2 by land and oceans is very poorly understood; and
- 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.

In the MDB context it could further be added that:

- Global Climate Model (GCM) forecasts for precipitation are almost equally distributed between positive and negative change – hence all that can be said reliably is that ‘it will be warmer and wetter OR warmer and drier’. However median results of an ensemble of GCM projections indicate a drying trend along an approximate north-south gradient, with the southern parts of the Basin facing the greatest drying trend.
- 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 with global climate change are not well understood and are poorly, if at all, replicated in GCMs.

6.4. Observations of Climate Change in the MDB

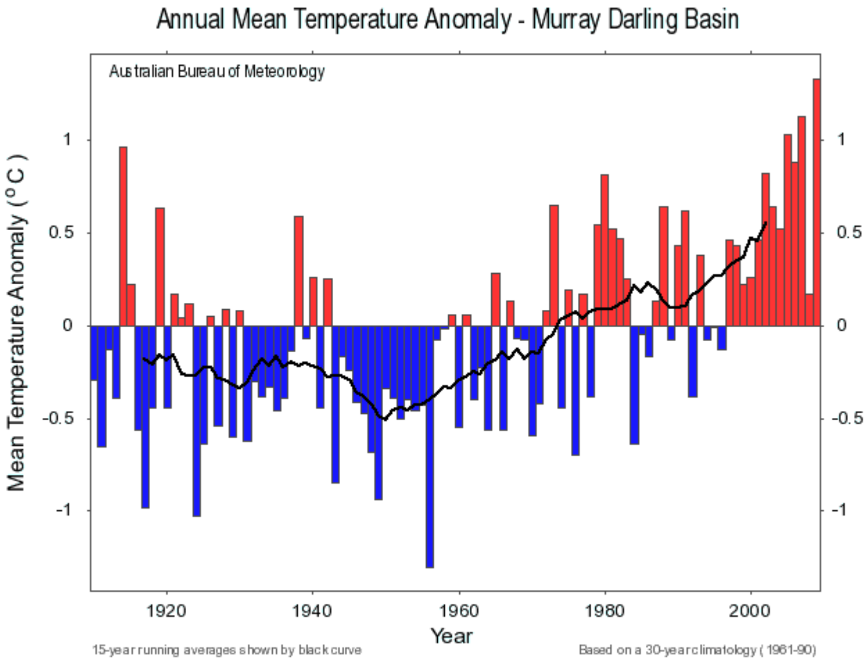
This section tabulates some observations of changes to the *climate system* in the MDB.

- **Table 6-1 Summary of observations of climate change in the MDB**

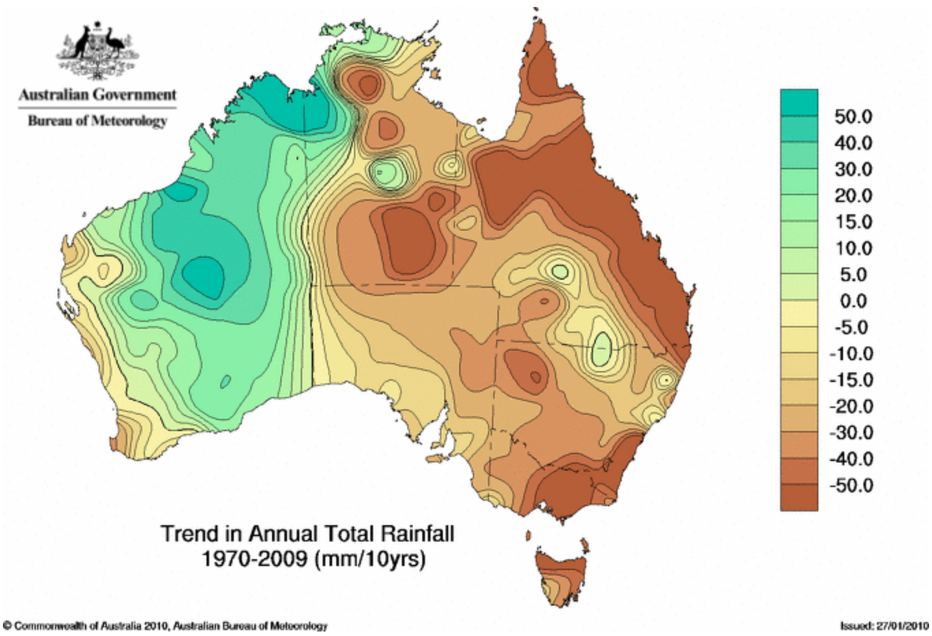
Aspect of the climate system	Observed change
Annual mean temperature	A general upward trend in temperature is observed since the 1950s with 2009 being the hottest year (**Figure 1;** BOM 2010**)**. The decadal mean temperatures in the MDB (2000-2009) shows an increase of 0.53°C over the previous decade (1990-1999). 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. However when viewed spatially (**Figure 2**), there is a clear trend of increased drying across most of the Basin, being highest in the south-east corner (~50 mm /decade). This trend is evident at other time scales but appears to have intensified since the 1970s. The spatial trend in heavy rain days for

	the Basin for the period 1970-2009 show a declining trend across the MDB. Seasonal temporal rainfall trends for the MDB show little long term temporal trend except for autumn, which shows a marked downward trend over the last 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.
Streamflow	Precipitation in the MDB over the past 10 – 12 years was significantly lower than the long term average, and has been accompanied by a 40% reduction in streamflow in the southern MDB, where the majority of runoff is generated. During the period 2000 – 2007, average annual inflow has been 4150 GL yr^{-1}. In 2006-07, the 12 month streamflow reached an historical low of 770 GL yr^{-1} to March 2007 (Cai and Cowan 2008; **Figure 3**). The average streamflow between 1998 and 2008 was 5,700 GL, substantially lower than the long term average of 11,600 GL yr^{-1} between 1892 and 1997 (Kiem and Verdon-Kidd 2010). Despite these observations of unprecedented low streamflow in the Basin, the attribution of the reduction to climate change is highly complicated. Streamflow is heavily influenced by land management practices, such as irrigated agriculture and forestry and water management regimes determining levels of diversions and water use from streams. Another confounding factor lies in the emerging understanding of the impact temperature change has on streamflow in the MDB. Determining plausible physical mechanisms underlying empirical temperature-streamflow relationships is subject to ongoing research (Yu *et al.* 2010).
Aspect of the climate system	**Observed change**
Flooding/Tropical cyclones	The flood seasonality for the north-east of the Basin shows predominantly summer/autumn floods events deriving from tropical troughs/lows (31 %) and remnants from tropical cyclones (12%) (Grootemaat, 2008). Trends in tropical cyclone activity in the Australian region (south of equator; 105-160°E) show that the total number of cyclones has decreased in recent decades.

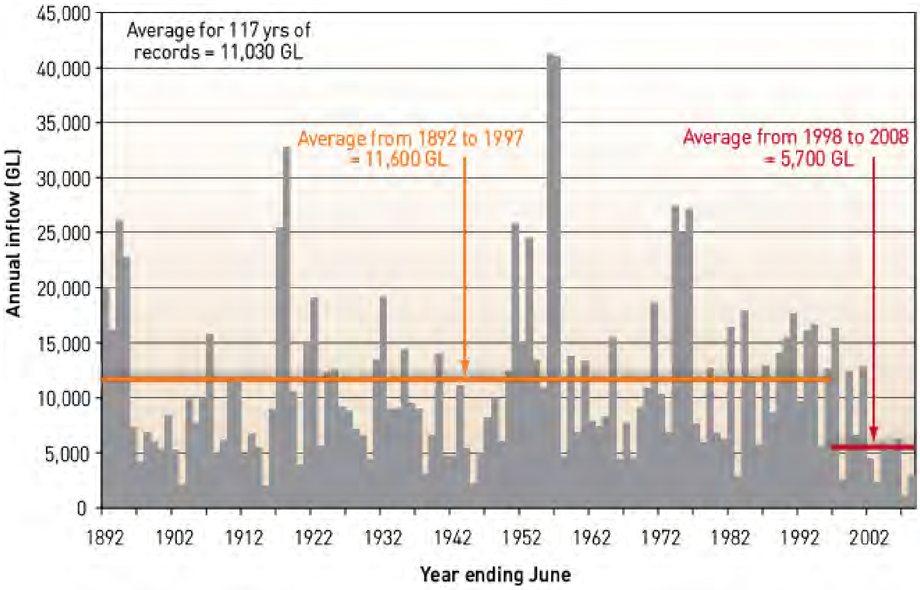
	However, the number of stronger cyclones (minimum central pressure less than 970 hPa) has not declined.
Drought	The relative frequency of El Niño to La Niña events within a 15-year moving window during the last 600 years show when more frequent El Niño events occur there are more likely to be periods of drought in Australia (Verdon-Kidd and Kiem 2010). This reconstruction indicates that more severe and prolonged periods of drought may 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 – 1945); 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 heat waves	The annual maximum and minimum temperatures for the MDB over the period 1910-2009 show an upward trend and approximate increase of 1C (BOM 2010). 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 heat waves (number of worst annual-three-day-heat wave indices) is increasing across eastern Australia (Deo *et al*. 2009).
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-east Australia has become drier; droughts have become hotter (Nichols 2004); and the number of extremely hot days has risen (maximum temperature > 40°C). 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 2 Annual mean temperature anomaly for the Murray-Darling Basin (1910-2009) with 15-year running average (black line)** (Source: http://www.bom.gov.au accessed 3 October 2010)



▪ **Figure 3 Annual rainfall spatial trend for the Murray-Darling Basin (1970-2009)** (Source: http://www.bom.gov.au accessed 3 October 2010)



- **Figure 4 Record of annual inflows to the MDB since 1892 (Kiem and Verdon 2010)**

6.5. Future climate projections

Forecasts of future climate change in the MDB are summarised in **Table 7** below.

- **Table 6-2 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.
Precipitation	The CSIRO 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 percent to little change in mean annual rainfall (CSIRO 2008).
Evapotranspiration	Wet Area Evapotranspiration in the MDB has been projected for the years 2030 and 2100 based on a prediction of the CSIRO-Mk3.5 GCM, under SRES marker scenario A1F1, under a high rate of global

	warming. 2030 predictions 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 >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.
Stream flow	The MDB Sustainable Yields Project estimates changes in runoff in the MDB to range from -33% under a dry extreme scenario, -9% under a median scenario, to a +16% 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% in 2070 but increases of 60% (2030) and 100% (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 – 2040, exceptionally hot years are likely to affect about 65% of the MDB and occur every 1.6 years on average; ▪ by 2010 – 2040 little change is likely in the frequency and areal extent of exceptionally low rainfall years; and ▪ by 2030, exceptionally low soil moisture years are likely to affect about 7% of the MDB, and occur about once every 13 years on average.
Extreme temperatures and heat waves	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 one for the southern-most part of the MDB (CSIRO and BOM 2007)
Aspect of the climate system	**Forecast changes in the MDB**
Bushfires	Climate change projections produced by 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% by 2020 and 15 – 70% by 2050 (Lucas *et al.* 2007).

6.6. Recent Advances in Understanding

Recent syntheses and investigations funded by MDBA are summarised in **Table 8** below. Most of this work is as yet unpublished.

- **Table 6-3 Recent synthesis studies funded by 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) has been made.
Anthony Kiem and Danielle Verdon-Kidd	Review of current understanding into 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, a La Niña event is not necessarily always associated with above-average rainfall in the southern MDB. 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 likely insignificant. Others, through spatial aggregation of the small-scale processes may lead to amplification or moderation of the larger-scale forcing.
Michael Roderick and Graham Farquhar	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 runoff as a function of two climatic factors, precipitation (P) and evaporative demand (E) and a third parameter (n) that encodes the catchment properties. The mean change is for a slight increase in *P* of 1% under A1B emissions which theory predicts with all else constant translates to a 2.6% increase in runoff. The mean predicted increase for E is 7%. The theory predicts that with all else constant this translates to an 11% decrease in runoff.
Peter Gell and collaborators	Palaeoclimate 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 last 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 for over a third of the 221 years since European settlement part or all the Basin has been in drought. Two long extended drought periods from 1795 to 1830, extending over 35 years, and 1980 to 2009, extending over 29 years show a complete alteration to the water cycle.
Tim Low	Climate Change, Weeds & 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 community to envision different futures. It is likely that institutional change would be required as part of the process of responding to this challenge.
Bonnie Bonneville, Julie Morris, Emma Collins, David Dettrick and	Impacts of Climate Change on the Murray–Darling Basin's Water Quality	Impacts of climate-related extreme events (prolonged droughts, bushfires, heat-waves, 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

Annie Sanderson		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 runoff), 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, and 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 are 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 changes on plant physiological and catchment ecohydrological processes in the high-rainfall catchments of the Murray-Darling Basin: A scoping study	This project explores the sensitivity of runoff, in the context of climate change, across the MDB to changes in five key ecohydrological parameters: annual precipitation, annual potential evaporation, average storm depth, catchment-average rooting depth, and atmospheric CO2 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 last thirteen 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 streamflow should logging cease in the higher rainfall, forested catchments of the MBD.

7. Implications and Future Actions

7.1. Implications arising from the four projects synthesised

This report describes the coordination and knowledge synthesis of four projects conducted under the Murray-Darling Basin Authority's Risks to Shared Water resources Program. The four projects are:

- Impacts of Climate Change on the People, Communities and Industry of the MDB;
- Impacts of Climate Change on the MDB's Water Quality;
- Risk of climate change impacts on salinity dynamics and mobilisation processes in the MDB; and
- Impacts of Climate on the Aquatic Ecosystems of the MDB.

The key findings and recommendations of these projects are provided in plain English form in the Executive Summary and are not repeated here.

7.2. Implications for the knowledge base – gaps and future directions

In this section a brief discussion is given to the current status of knowledge, including areas where knowledge well established, still contested and relatively poorly addressed.

Topic	Status
Climate Science	
Global climate change overview	Climate change is a global phenomenon and progress in global climate science is an important contributor to the knowledge base for the MDB. The IPCC is the major process for building consensus on the state of knowledge and communicating the science. Their most recent global review was published in 2007, with science inputs up to around 2005. A number of science organisations continuously update some aspects of climate science whilst normal journal publication processes add to the knowledge base. Some researchers suggest that the IPCC (2007) is conservative in its projections. This is particularly true for sea-level rise, which did not

	incorporate ice flow contributions, and hence substantially underestimates future projections. The Royal Society has made a useful contribution by identifying the aspects of climate science that are well understood, still debated and virtually unknown. There is however no new science, since 2007, that significant reduces the validity of the global warming – climate change hypothesis.
Current understanding of MDB climate patterns and causal processes	There has been rapidly improving knowledge of the drivers or modes that are responsible for climate across the MDB. These include ENSO (the most important driver of inter-annual variability across the MDB), IOD and SAM (regionally important during some seasons), PDO (important regulator of decadal climate variations in the MDB) and the STR. Progress has been made on the relative contributions and combinations of these drivers to specific climate sequences, such as droughts or observed seasonal variations. The interaction between global warming, regional modes and local weather is the subject of ongoing research; whilst complex some progress has been made for example in linking the intensity of the STR to global warming. Land surface – atmospheric coupling is another area where progress has been made, for example illustrating the effects of vegetation clearing on regional temperatures. The feedback of land use/management into climate projections is a fertile are of research, albeit second-order effects.
Palaeoclimate in MDB	A range of palaeoclimatic tools have been used to construct a picture of past climate in the MDB over the past few thousand years. This is contributing to a broader understanding of climate variability, including the recognition of past drought periods extending over 50 years. Such information is valuable when attempting to comprehend droughts within the instrumental record, and provides insights to thinking about the relative contributions and interactions of climate change and climate variability.
NRM impacts of climate change in the MDB - observations and projections	
Temperature, heatwaves	Good quality observational data for many aspects of temperature are readily available through the BOM website for the MDB. Temperature projections to 2100 are reliant on GCMs and have been reported via the IPCC and BOM/CSIRO climatechangeinaustralia website. Some

	scientists regard the IPCC temperature predictions as conservative as the models do not take into account important feedback mechanisms, or the decreasing capacity of carbon sinks as temperatures increase. Extreme events such as heatwaves are difficult to estimate. The potential for abrupt temperature changes (e.g. several degrees in one decade) has not been given much attention.
Rainfall, rainfall intensity, cyclones	Good observational records of rainfall are available for the Basin. Some rainfall intensity statistics are also available via the BOM website. With respect to GCM projections for rainfall and rainfall intensity, there is some confusion and debate. GCMs give a wide range of rainfall predictions, both positive and negative, and their level of agreement is poor. Seasonal rainfall projections by GCMs do not match observations. Rainfall intensity is also a subject of debate, with projections differing from observations. Remnants of tropical cyclones, tropical troughs/lows and extratropical storms are an important climatic feature in the northern Basin. Clear trends in cyclonic activity are not all that apparent and there is little information on how cyclone tracks may change in the future.
Pan evaporation, evapotranspiration	Trends in pan evaporation have been the subject of considerable discussion in the MDB. Further work on understanding this important variable is warranted.
Plant physiology and ecohydrology	Understanding of plant physiological changes to climate change (including CO_2, temperature, rainfall, potential evaporation, soil moisture) and hydrological implications is very rudimentary in the southern hemisphere and the MDB. The scoping work conducted to date suggests these factors are important and merit further research.
Soil moisture	Soil moisture is modelled, mapped and reported annually or by season across Australia and the MDB. Surface and subsoil moistures are estimated. The subsoil tends to reflect longer term rainfall trends, while the surface soils more reflect recent rainfall conditions. Soil moisture is important for farmers and also the hydrological functioning of catchments.
Groundwater, recharge,	An increasing amount of research attention is being given to climate change impacts on groundwater recharge. Results to date suggest that

sw/gw	recharge is sensitive to rainfall and rainfall intensity and to some extent evapotranspiration. Streams fed by groundwater are vulnerable to climate change impacts.
Runoff/Streamflow/flooding/water balance	Streamflow observational records are becoming available via BOM. These records are often complicated by multiple land and water use activities directly and indirectly affecting streamflows. It is hence difficult to separate out climate change impacts. Recently some gauging sites have been selected as longer term monitoring sites. Future projections for streamflow are highly dependent on future projections for precipitation and to a lesser extent evapotranspiration. Temperature has been found to be correlated to streamflow, although the cause and effect mechanisms are not known. Plant physiological responses have also been shown to be important in streamflow responses.
Droughts	Droughts from the instrumental record, back to early settlers and then in the palaeoclimate have been collated and analysed. Comparing the three major droughts since 1900, an interesting feature of the Big Dry was lower runoff for the equivalent reduction in rainfall. Several lines of research are being pursued, including temperature effects, annual and seasonal variations, number of rain days, rainfall intensities, and land use effects contributing to water interception.
Dust storms	Dust storms are most prevalent in the drier parts of the MDB but can carry soil, organic material and a range of contaminants large distances in a short time, depositing some materials in various water bodies. As desertification or aridification increases with climate change, the potential for dust storms may increase too. Whilst some good research on dust storms has been conducted in the past, the specialist research groups have been wound up.
Salinity	Observational evidence shows large scale mobilisation of soil salts has decreased over the last two decades as water tables have lowered in response to a drier climate, hence reducing discharge to streams. However salinity instream and in wetlands have increased in some locations due to decreased flows (and hence dilution) and evaporative concentration. Hypersaline remnant pools are examples of this occurring. Future projections are similar to recent trends, with the

	caveat that a dry period in which salt accumulates in soils, followed by flooding, could release these additional stored salts.
Water quality	The impacts of climate change on a range of water quality parameters, mediated through land and water management and uses, has been reviewed for different regions across the MDB and risk rated. Water quality has been shown to be susceptible to extreme climate events, which have been given particular attention in the analyses.
Aquatic ecosystems	Flora, fauna and ecosystems are particularly susceptible to changes in temperature and flow regimes brought about by global warming. Some 'robust' species will be favoured under climate change whilst many native species will be disadvantaged. Research to date is rudimentary and requires further investment.
Invasive pests and weeds	The response of a range of invasive pests and weeds to climate change has been well reviewed. Arguments for proactive action have been provided.
Bushfires	The knowledge of the impacts of bushfires on water yield and water quality is growing. However links between climate change and bushfires, and feedback processes, are crude at present.
Biodiversity & ecosystem services	Relatively little work has been done in the MDB focussing on the impacts of climate change on biodiversity and the provision of ecosystem goods and services. The international literature shows that all biotic groups are being affected by climate change and ecosystem goods and services are at risk.
Impacts of Climate Change on Industries	
Irrigated agriculture	Models of the economic impacts of climate scenarios have been conducted for all irrigation regions of Australia. This takes into account water trading where water markets exist.
Dryland agriculture	Impacts of different climate scenarios on wheat farming and farm prices have been undertaken.
Forestry and Plantations	Impacts of climate change on native forests and plantations in the water resources context have been scoped, and broad conclusions

	drawn.
Tourism	Preliminary work on the impacts of climate change on tourism (a large industry) in the MDB has been undertaken.
Impacts of Climate change on People and communities	
Irrigation communities	The impacts of climate change on irrigation communities and their ability to adapt to these changes has been workshopped. Important conclusions about the current stress and wellbeing of rural communities, and their adaptive capacity have been elucidated.
Indigenous communities	The perspectives of indigenous communities on climate change have been documented. A wide range of issues has been identified, which may be partially addressed through a growing interest in indigenous water rights.

7.3. Concluding remarks

It clear that climate change is now an integral part of environmental, economic and social futures of the MDB. 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 over-riding 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) who 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 the above quandary, modellers have developed future climate scenarios that capture both a range of future GHG 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 above 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: 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; and 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 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 needed.
- 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 in part due 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 indications that some of these modes are being influenced by global warming. Research on these aspects of climate variability and interactions with climate change are 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 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 palaeoclimate records as a means of understanding and assessing impacts of past and future climate change, particularly given the limitations on 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 may have significant impacts on industries and communities. Clear, well-argued priorities for research to meet the needs of all sectors of the community should be agreed and financially supported.

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Appendix A Inception Workshop Agenda and Minutes

AGENDA

Date: Tuesday 23 March 2010
Time: 0930 -1630
Venue: SKM office, 214 Northbourne Ave, Canberra (parking available)

11. Welcome & Introductions (NS)
12. Background to the Risks Program and any new developments (MM)
13. Timelines - check on meeting MDBA deadlines
14. Project information exchange (project leaders to present what they intend to do in 20 minutes via powerpoint)
    - 14.1 Water Quality
    - 14.2 Salinity
    - 14.3 Aquatic ecosystems
15. Climate scenarios and risk framework (discuss climate change drivers – climate, water & land; use of climate scenarios and data availability; risk framework) (NS lead)
16. Discuss emphasis on literature review/interpretation vs new analyses (NS lead)
17. Discuss nature of outputs and synthesis products (including data, sites, regions, north-south, basin, GIS, risk colour coding etc, journal publications) (NS lead)
18. Repeatability (discuss what will be required for repeat analyses to be conducted with new information) (NS lead)
19. Relationship and value-adding to Basin Planning work (MM)
20. Any other business arising
21. Close

MINUTES

Meeting held Tuesday 23 March 2010 at SKM office, 214 Northbourne Ave, Canberra

Attendees:

Alice Shields	MDBA
Mathew Maliel	MDBA
Nick Marsh	Aquatic ecosystems project
Bonnie Atkinson	Water quality project
Keith Collett	Salinity project
Ray Evans	Water quality and salinity projects
Nick Schofield	SKM – project coordinator
Steve Purbrick	SKM - support

Outcomes

22. **Background to the Risks Program and any new developments**

    MM provided a brief history of the Risks Program and made the following points:

    - Other risk projects of interest are: Macquarie Marshes case study (UNSW) and basin-wide desktop sulphur study (Richard Bush, Southern Cross Uni)
    - The new climate scenarios being used in the Basin Plan are confidential and unlikely to be available for these projects
    - The MDBSYP scenario data may also be difficult to access as people have moved on.
    - Direct communications with MDBA staff is encouraged, ensuring MM, AS and NS are kept in the loop.

23. **Project information exchange**

    The project presentations Water Quality, Salinity, Aquatic ecosystems were given, allowing a useful interaction between projects. Outcomes included:

    - AS would seek to obtain the latest draft of the MDBA's Water Quality and Salinity Plan for two relevant projects
    - Teams would nominate their focus/case study sites to see where opportunities for joint analysis could be undertaken
    - Recognition that a 'dry scenario' was a positive for salinity
    - The aquatic team would broaden their scope from lowland rivers to all major river types
    - The new MDBA Basin Plan regions should be used where possible.

24. **Climate scenarios and risk framework**

NS presented a summary of current climate change science applicable to the MDB based on SEACI and work conducted in MDBA's science reviews. He then proposed alternative approaches to formulating scenarios and risk assessments for the projects. The team concluded that 6 scenarios would be required to meet requirements:

A. MDBSYP 'wet' climate scenario

B. MDBSYP 'median' climate scenario

C. MDBSYP dry' climate scenario

D. MDBSYP historical 1895-2006 baseline

E. MDBSYP recent 1997-2006 baseline

F. Drier than E.

The team would also examine a wide range of climate change features (for atmospheric, water/hydrology and land use drivers) to ensure the ones most pertinent to the topic in question are adequately addressed.

25. Discussion on literature review

The team agreed that a thorough literature review would be conducted in each project to ensure a clear articulation of current knowledge. The importance of clearly identifying gaps for future work was also noted.

26. Nature of outputs and synthesis products

MM indicated that the MDBA would be seeking:

- Final reports that are peer-reviewed and suitable for publication on the MDBA website
- To establish a independent peer-review panel
- To encourage teams to prepare journal papers where appropriate
- Clear and concise summary documents that can be readily converted into communication products like factsheets
- To complete a synthesis of all climate risk projects when completed and use this as an input to a risk assessment framework (separate MDBA task)

27. Repeatability

Team members agreed that the following will be carefully documented to allow efficient repeatability of analyses with new information, scenarios etc:

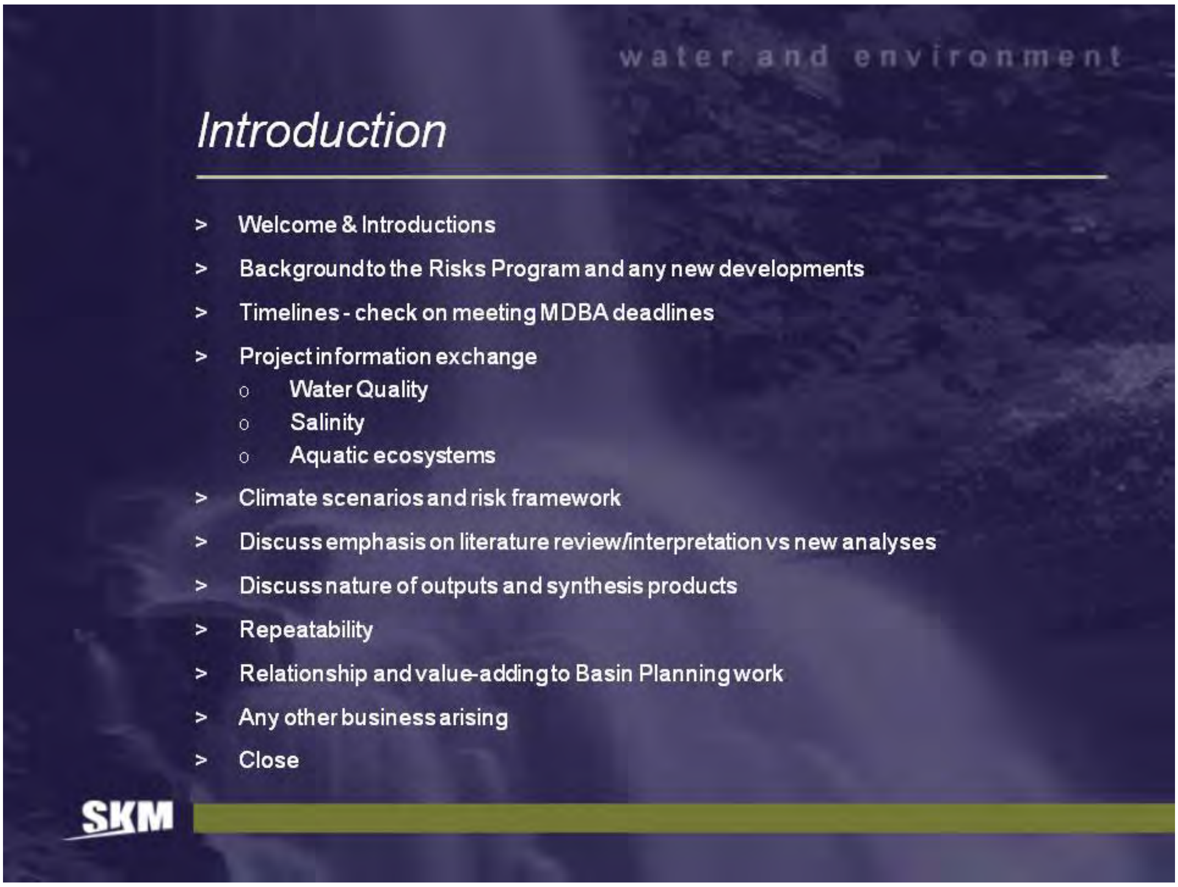
- Methods
- Conceptual models
- Physical models
- Data (as per MDBA protocols)

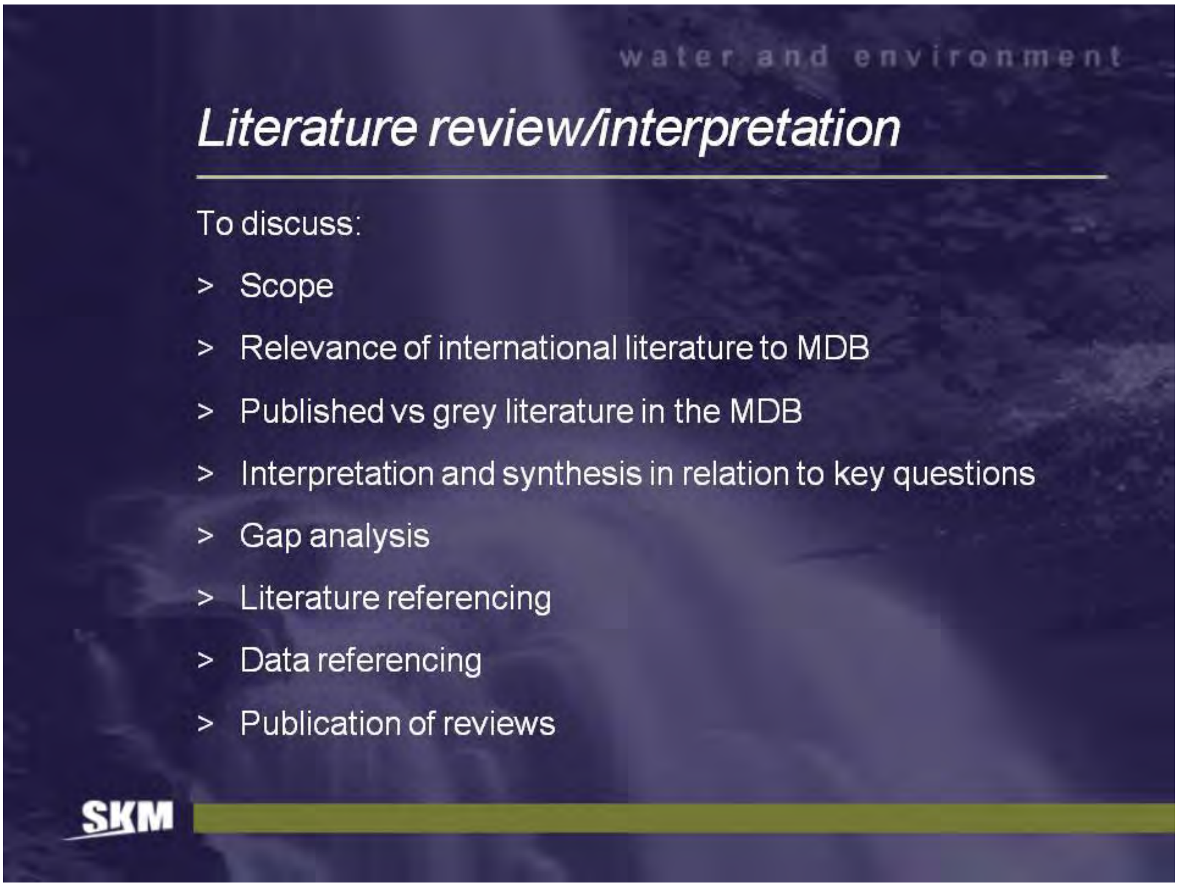
- Assumptions
- Hypotheses

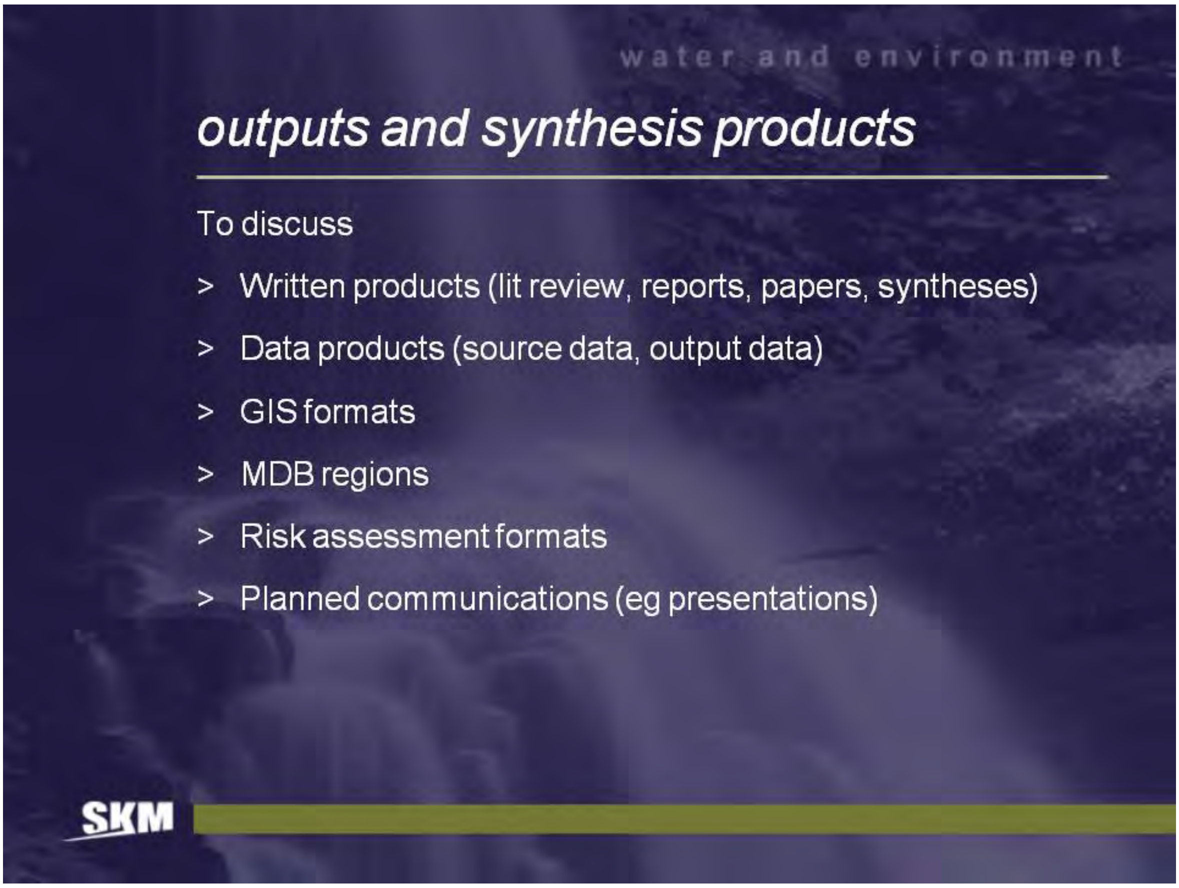
28. Relationship and value-adding to Basin Planning work

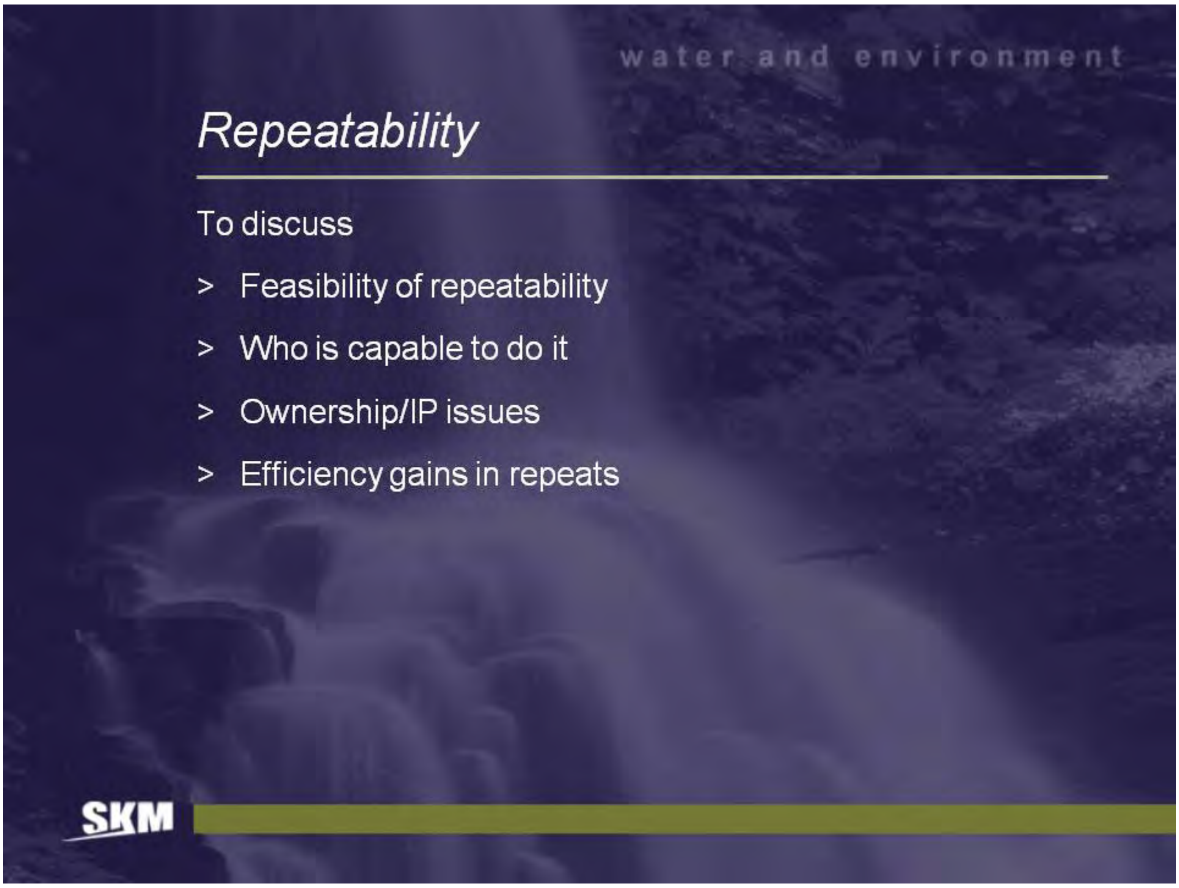
It was noted that Basin Planning staff may be difficult to engage up to 30 June. However it would be worthwhile to keep relevant groups in the loop with updates via MM and AS. Opportunities for face-to-face briefings could also be arranged should there be sufficient merit.

NS 23.3.2010


water and environment
Introduction
> Welcome & Introductions
> Background to the Risks Program and any new developments
> Timelines - check on meeting MDBA deadlines
> Project information exchange
o Water Quality
o Salinity
o Aquatic ecosystems
> Climate scenarios and risk framework
> Discuss emphasis on literature review/interpretation vs new analyses
> Discuss nature of outputs and synthesis products
> Repeatability
> Relationship and value-adding to Basin Planning work
> Any other business arising
> Close
SKM


water and environment
Literature review/interpretation
To discuss:
> Scope
> Relevance of international literature to MDB
> Published vs grey literature in the MDB
> Interpretation and synthesis in relation to key questions
> Gap analysis
> Literature referencing
> Data referencing
> Publication of reviews
SKM


water and environment
outputs and synthesis products
To discuss
> Written products (lit review, reports, papers, syntheses)
> Data products (source data, output data)
> GIS formats
> MDB regions
> Risk assessment formats
> Planned communications (eg presentations)
SKM


water and environment
Repeatability
To discuss
> Feasibility of repeatability
> Who is capable to do it
> Ownership/IP issues
> Efficiency gains in repeats
SKM


water and environment
Relationship to basin planning
To discuss
> Awareness of Basin Planning and other MDB work
> Arrangements for arranging discussions/accessing data
> Synergies/ value adding opportunities
SKM

Appendix B Project Synopses

CD2B: Impacts of Climate Change on the Aquatic Ecosystems of the MDB Synopsis

Team members

Member	Role	Skills	Email	Phone	Mob
Dr Fran Sheldon	Project manager	Freshwater ecology, dryland rivers including Murray-Darling Basin rivers, macroinvertebrate ecology, hydrological analysis	f.sheldon@griffith.edu.au	07 3735 3914	
Dr Nick Marsh	Team member	Environmental engineering, ecological modelling, hydrological analysis	nick.marsh@yorb.com.au	0421 616 087	
Dr Nick Bond	Team member	Freshwater ecology, ecological modelling, hydroecology and hydrologic analysis	Nick.Bond@sci.monash.edu.au	03 9905 5606	
Dr Mark Kennard	Team member	Freshwater ecology, environmental flow management, hydroecology and hydrologic analysis	m.kennard@griffith.edu.au	07 3735 7401	
Dr Wade Hadwen	Team member	Freshwater ecology, ecosystem processes, climate change ecology	w.hadwen@griffith.edu.au	07 3735 3987	
Dr Sam Capon	Team member	Riparian and floodplain vegetation ecology, dryland rivers including Murray-Darling Basin rivers, climate change on aquatic systems	s.capon@griffith.edu.au		0402 217 899
Sylvain Arene	Team member	Software engineering, ecological modelling	s.arene@griffith.edu.au	07 3735 6703	

Scope

- MDB wide
- Up to 20 sites of high ecological value
- Up to 30 species
- 3 climate scenarios + 1 reference scenario
- Rivers & streams, groundwater systems, terminal and floodplain lakes and wetlands
- Both aquatic flora and fauna

Approach/methods

Literature review will be conducted on the aquatic ecosystem impacts of the given climate change scenarios. The review will cover general impacts on ecological systems and where possible specific impacts in MDB. The review will cover impacts associated with all aquatic ecosystem types within the MDB: rivers & streams, groundwater systems, terminal and floodplain lakes and wetlands. Review will include both aquatic flora and fauna.

Habitat suitability modelling for up to 30 species across up to 20 sites of ecological significance in the MDB, for 3 climate scenarios. Uses eWater CRC 'Eco-Modeller' tool with 'Generic Species Plugin'.

Climate inputs required

- 3 specified alternative climate scenarios
- An additional reference 'un-impacted' scenario. This is to allow assessments relative to 'pre-development' conditions.

Other inputs required

- MDBA to provide daily time step flow series for each scenario as well as modelled pre-development (natural) scenario for each of the key sites. (Project team is familiar with the flow scenario datasets).
- MDBA to confirm 'commence to flow thresholds' required to fill wetlands.
- Nomination of up to 20 significant sites across the MDB that cover the range of geographies and aquatic ecosystem types. Ramsar sites + sites nominated by MDBA. Proposed list put forward by GU.
- Identify important species in the categories 'freshwater fish', 'water dependent vegetation' and 'water birds'.

Outputs generated

- Habitat availability under CC scenarios
- Water requirements of the life history stages of each species in terms of: magnitude, duration, timing, return period, rate of change.

- Species habitat preference models (with scientific rigour confidence score)
- ‘Potential suitability of habitat for species X at location Y under CC scenario A’
- Risk Analysis: ‘Likely persistence of species X at location Y under CC scenario A’
- Impact of CC between species, groups of species, geographic locations and scenarios.
- GIS framework (possible) for location matrix of habitat availability scores for species for each scenario.

Deliverables/products

1. Literature review on the aquatic ecosystem impacts of the given climate change scenarios. Review will cover general impacts on ecological systems and where possible specific impacts in MDB. The review will cover impacts associated with all aquatic ecosystem types within the MDB: rivers & streams, groundwater systems, terminal and floodplain lakes and wetlands. Will cover both aquatic flora and fauna.
2. Final report summarising the climate change impacts on the aquatic ecosystems of the MDB based on predictive habitat models for selected species at selected locations.
3. Predictive habitat assessment models that could be updated in future with more information, more species, more sites or alternative CC scenarios.

Communication plan

Not specified

Repeatability of method with new climate scenarios or new information

A quantitative and repeatable analysis of the likely impact of CC on the key water requirements of important species.

A modelling approach whereby scenarios can be applied to different species and locations.

In future can re-run for new: species, locations, scenarios.

Links to other risk projects

- Same climate-flow scenarios could be used for water quality and salinity.
- Impacts on ecosystem health by water quality/salinity needs to be integrated with water quantity and temperature for more complete assessment

Links to other MDBA work

1. Basin Planning – ecological watering plan. There has been work done on identifying the key environmental assets across the Basin and their watering requirements. This may have progressed to examining the impacts of climate scenarios?

Links to other work outside MDBA

1. Project will be aligned with the CSIRO Cluster funding research program 'Ecological Responses to Altered Flow Regimes' led by Prof Stuart Bunn, starting July 2010.
2. Murray Flows Assessment Tool project.
3. CSIRO project for NWC 'Ecological Outcomes of Flow Regimes in the MDB'

CD2C: Impacts of Climate Change on the People, Communities and Industries of the MDB Synopsis

Team members

Member	Role	Skills	Email	Phone	Mob
Prof Quentin Grafton	Leader + industry	hydrologic-economic modelling, agricultural, resource and environmental economics	Quentin.Grafton@anu.edu.au	02 6125 6558	
Paul Ryan	People & community	community and public facilitation	**paul.ryan@grapevine.net.au**		
Chris Miller	People & community	social analysis and community development	**chris.miller@flinders.edu.au**		
Fiona Verity	People & community	social analysis and community development	**fiona.verity@flinders.edu.au**		
Dr Michael Ward	industry	agricultural, resource and environmental economics	**Michael.ward@anu.edu.au**		
Dr William Nikolakis	indigenous	indigenous research	**William.nikolakis@anu.edu.au**		
Jared Dent	industry	agricultural, resource and environmental economics			
Qiang Jiang	industry	hydrologic-economic modelling, agricultural, resource and environmental economics			
Mavis Zutshi	People & community	community and public facilitation			
Angella Duvnjak	People & community	community and public facilitation			

Drew Collins (BDA)	industry	agricultural, resource and environmental economics			

Scope

People impacts: demographics, community viability & resilience, community vulnerability and adaptive capacity, cultural values, social cohesiveness and capital, economic development and public infrastructure

Industry impacts: agriculture (irrigated and dryland), forestry, aquaculture, food and fibre processing & value adding, construction, transport, tourism, public and private sector service provision

Communities: water-dependent, non water dependent, indigenous

Approach/methods

'Industry' Team (Grafton, Ward, Collins, Dent and Jiang) to undertake detailed modelling of the impacts of climate change on irrigated and dryland agriculture in the catchments of the Basin and also a broad-scale evaluation of the economic impacts across the Basin in other sectors such forestry

'Peoples and Community' Team (Ryan, Miller, Verity Ryan, Zutshi and Duvnjak) who will conduct in-depth discussions in six communities (three water dependent and three non-water dependent) and a social researcher with extensive experience working with aboriginal communities on water issues (Nikolakis).

Selecting communities criteria: BRS data on resource reliance, livelihood reliance, social vitality, social stress and social inclusion; north and south Basin; agricultural activities; proximity to key environmental assets; relative importance of surface and groundwater; communities currently being profiled by MDBA.

Models: irrigation and dryland agricultural models that enable water use, land use and land value to be simulated under climate change.

Community workshops: identify community strengths and capacities, assess impacts of water reduction, potential options

Indigenous communities: interact with all 10 indigenous nations re managing climate change.

Scale of analysis: SYP regions

Climate inputs required

Not specified beyond the 3 CC descriptions

Other inputs required

Water reduction scenarios for each region.

BRS economic and social data.

Outputs generated

- Economic impacts of CC on irrigated and dryland agriculture
- CC impacts and needs of indigenous communities
- Socio-economic impacts of CC on non-agricultural sectors
- Implications and opportunities for the management of the Basin's water resources
- Advice on how to follow up the study in the future
- Recommendations to MDBA

Deliverables/products

1. Final technical report
2. Plain English summary

Communication plan

A summary of the findings will be written in a non-technical way and made widely accessible.

Journal publications.

Repeatability of method with new climate scenarios or new information

All approaches and methods used will be fully documented to ensure repeatability of the research and the risk assessment.

Advice on how to follow up the study in the future.

Links to other risk projects

This project is based on reduced water availability. It doesn't currently include a socio-economic assessment of changing water quality or ecosystem health.

Links to other MDBA work

- Recent review of socio-economic studies for MDBA …BDA & Grafton

- Socio-economic impacts of Basin Plan

Links to other work outside MDBA

Quiggin et al (2008) model of economic returns across a range of CC scenarios for Garnaut Review

Grafton & Jiang (2010) model the impacts of reduced inflows across whole basin.

Adamson et al (2009) economic impacts of uniform reduced inflows vs droughts

Mallawaarachchi 2008 regional differences in economic impacts of CC

Connor et al 2007 low cost adaptation strategies

Jones et al 2007 economic reduction relative to water reduction

Dixon et al 2009 inter-regional water trading and reduced flows – economics

Goesch et al 2009 effects of economic diversity (or specialisation) on economic impacts of CC

Risk of Climate Change Impacts on Salinity Dynamics and Mobilisation Processes in the Murray-Darling Basin

Team members

Member	Role	Skills	Email	Phone	Mob
Anthony Brinkley	Project Director Management options				
Greg Holland	Project Manager + risk assessment	Groundwater specialist	GHolland@skm.com.au	02 6246 2708	
Keith Collett	Scenario modelling	Groundwater specialist			
Tony Sheedy	Scenario modelling Management options	Waterways Engineer			
Martin Brownlee	Risk assessment	Risk Assessment, Data and Catchment Processes			
Henry Chaplin	Mapping	Map and Spatial Production			
Craig Clifton	Risk assessment	Climate Change Specialist			
Ray Evans	Scenario	Principal Hydrogeologist			

	modelling Management options				
Jodie Pritchard	Scenario modelling	Data and Catchment Processes			
Rose Mannik	Scenario modelling	Data and Catchment Processes			
Ian Varley	Scenario modelling	Data and Catchment Processes			
Rebecca Lett	Scenario modelling	Water resources engineer			
Bob Newman	Technical Reviewer Scenario modelling Management options	Groundwater specialist			

Scope

Climate change risks expressed through changes to groundwater and surface water hydrology, both of which are the fundamental drivers of salt mobilisation and river dilution capacity associated with the mobilisation

Risks with the extremities of the climatic sequence: the extended dry periods when surface water storage levels are low providing little opportunity for dilution flow; and during wet periods when increased salt is mobilised from tributary valleys, irrigation areas and the Mallee floodplain

Salinity risks to environmental values (or beneficial uses), including aquatic ecosystems, raw drinking water and irrigated agriculture

Water salinity impacts to rivers, wetlands, reservoirs and aquifers

Our approach will assess the risks at valley or irrigation area scale (i.e. sub-region) for each landscape form. The focus for detailed assessment will be those sub-regions where historical data indicates salt mobilisation as most prevalent, however the methodology will be applicable to every sub-region if an assessment of every sub-region was considered necessary.

Approach/methods

i. Literature review of the knowledge and understandings of the science and research relating to the potential salinity impacts of climate change on the Basin's water resources within the context of key landscape forms. This will provide a baseline understanding of variations in climate change impacts on basin hydrology and salt mobilisation, and the main drivers of salt load and dilution flows within range of landscape forms. The review will consider, but will not be limited to, the following factors: infiltration of surface water to groundwater; dynamics (vertical/lateral) of groundwater, salt concentration of groundwater; accession of groundwater back to surface water; effects on groundwater dependent ecosystems; dilution capacity; and, land management / vegetation.

ii. Confirm the climate scenarios and their implications on surface water hydrology and groundwater recharge across broad categories of landscape within the MDB

iii. *Conceptual models* will be clearly defined to tease out the indirect and direct impacts of climate change as they relate to generalised landscape forms, providing the MDB with a robust basis to focus future priorities and informing new strategies and plans.

iv. Classify the landscape forms for which models are proposed covering: the upland catchments in Queensland, NSW and Victoria, and the northern basin upstream of the Darling at Wilcannia; the Irrigated Riverine Plains of NSW and Victoria; the Mallee Zone (irrigated and dryland); the River Murray floodplain in the Mallee Zone; and the shared rivers (Murray and Darling).

v. Scenario Modelling to establish the implications of climate scenarios in terms of in-river salinity outcomes in key landscapes across the basin. The approach will be to consider the climate driven salt mobilisation processes in the individual sub-regions selected to ensure the detailed efforts in scenario modelling are focused towards valleys or irrigation areas posing the greatest salinity threat.

vi. Recommendations on options for a more up-to-date and representative benchmark period, or alternative approach

vii. Risk ratings for different landscapes under climate change scenarios including: (i) short term risks to thresholds for key beneficial uses (ie aquatic ecosystems, raw drinking water and irrigated agriculture), (ii) Long term risks to "average salinities" within the shared water resources (ie over benchmark period)

viii. Assess management options to mitigate risk.

Climate inputs required

At least three climate change scenarios; scenarios that are significantly different from the 1975-2000 period.

Utilising data sets secured from the Murray Darling Basin Sustainable Yields Project, SKM will establish the climatic scenarios upon which the salinity assessments are to be established. It is anticipated that it will be necessary to liaise closely with the Climate Change Projects Coordinator to ensure consistency in the application of climate change data sets across other climate change projects. However SKM currently anticipates that the Murray Darling Basin Sustainable Yield climate scenarios ("Wet") ("Dry") and possibly ("Mid") will be used to reveal the range of salinity impacts e.g. salinity scenarios, irrigation scenarios, changes to the irrigation landscape, etc.

Other inputs required

nil

Outputs generated

- Literature review
- Data gaps and modelling limitations

- Documented understanding of: Understanding variations in climate change impacts on basin hydrology and salt mobilisation; Main Drivers of salt load and dilution flows within range of landscape forms; Definition and mapping of landscape form.
- Agreed landscape forms and modelling scale and documented suite of models
- Agreed Risk Assessment Framework
- Documented risk assessment
- Consequence of salinity outcomes for the Basin's water quality
- Likelihood of high salinity outcomes (use climate change analysis and guided by existing data sets) for each Landscape Form given main drivers identified in literature review.
- Options for a future BSMS Benchmark Period
- Risk ratings for different landscapes under climate change scenarios including: Short term risks to thresholds for key beneficial uses (ie aquatic ecosystems, raw drinking water and irrigated agriculture), Long term risks to "average salinities" within the shared water resources (ie over benchmark period)
- Options for future management arrangements to address salinity risks.

Risk assessment

SKM will discuss with the MDBA and the Coordinator (see section 3.4) the selection of a risk assessment framework appropriate to the climate change impacts of salt mobilisation and dynamics. The decision on the preferred framework will either be the application of an existing preferred risk assessment tool provided by the MDBA, or a refined framework emanating from consideration of the Australian Standard (AS4360) that provides a national model for the assessment of Risk, and the 2008 MDBC Risk Management Framework developed by SKM.

The risk assessment will guide the MDBA in understanding those landscapes and potentially sub-regions that pose the greatest threat to water salinity under climate change scenarios. It will also enable the Basin Planning Division to consider whether Salinity Targets being developed under the Basin Plan to protect aquatic ecosystems, raw drinking water and irrigated agriculture, are likely to be achieved under climatic scenarios and whether achievement is likely to require investment.

Deliverables/products

Draft final report

Final Report

Presentation

Communication plan

A communication strategy will be developed at the project's inception. The final report will include an executive summary which will concisely and effectively summarise the findings and outputs of the entire project. The report will be written in "plain English" so as to form the basis for a policy document if required by the MDBA. We will also deliver a final presentation to the MDBA (if requested) upon completion of the Final report and this project. Additional stakeholders (such as the Basin Salinity Management Advisory Panel) may be invited if deemed appropriate by the MDBA.

The communication plan will stipulate engagement at the following points in the project:

- At the project kick off and inception.
- After adoption of the proposed climate change scenarios.
- During the determination of the agreed risk assessment framework.
- Draft report stage (influencing the final report and Timelines).

Repeatability of method with new climate scenarios or new information

The risk assessment framework and any models we develop will be able to be reapplied to assess changes in risk under future shifts in water sharing arrangements that may arise from the Basin Plan SDL or Environmental Watering Plan.

Links to other risk projects

Effective coordination will capture key synergies between this project and the related suite of climate change projects

Links to other MDBA work

- Water Quality and Salinity Management Plan
- Basin Salinity Management Strategy
- Independent Audit Group – Salinity
- The Murray-Darling Basin Sustainable Yields Project – providing climate change scenarios
- The Murray-Darling Basin Commission work on risks to shared water resources – providing concepts on the assessment of risks
- Available work completed on the Salinity Targets review – providing guidance on salinity implications for particularly parts of the Murray-Darling Basin landscape including the northern Basin, upland catchments, Riverine Plains and the Mallee zone.
- Development of Sustainable Diversion Limits by the MDBA.

Links to other work outside MDBA

- formulation of Water Resource Plans required to be developed by each Basin state

- National Water Quality Management Strategy

Issues for discussion

Impacts of Climate Change on the Murray-Darling Basin's Water Quality

Team members

Member	Role	Skills	Email	Phone	Mob
Dr Tony Church	Project director	Practice Leader for water quality management	tchurch@skm.com.au	**02 99282384**	
Dr Bonnie Atkinson	Project manager	water quality scientist	blatkinson@skm.com.au	03 9248 3064	**0417318066**
Dr Ray Evans	**Hydrogeologist**	Groundwater quality specialist	WREvans@skm.com.au	**(02) 62462704**	
Dr Simon Treadwell	**Senior Ecologist**	Ecological risk assessment specialist	Streadwell@skm.com.au	**(03) 92483198**	
Simon Lang	**Water resource engineer**	Climate change modeller and hydrologist	slang@skm.com.au	**(03) 92483068**	
Julie Morris	**Ecologist**	Communications	jmorris@skm.com.au	**(03) 92483018**	
Jane Edwards	**Spatial analyst**	Spatial analyst	JXEdwards@skm.com.au	**(03) 92483550**	
Prof Mike Grace	**Technical Review**	water quality	Mike.grace@sci.monash.edu.au	**03 99054078**	

Scope

Water resources: rivers, streams and wetlands; drinking water reservoirs and irrigation infrastructure; and groundwater aquifers. Project will target the high priority water ways – focussing on the key water issues within the catchment and pulling out some example sites. There will not be an individual assessment for every wetland, stream, reservoir etc.

Climate impacts: temperature change (rise), changed rainfall amounts, changed rainfall patterns, changed water balance, changed vegetation and land-use (where information is available from other studies).

Water quality parameters: dissolved oxygen, temperature, pH, salinity, nutrients, suspended solids and algal counts.

Beneficial uses: aquatic ecosystem health, drinking water quality, irrigation supply, recreation

Approach/methods

Literature review: In this key task we will collate and review a range of scientific literature and consult with key researchers (as identified by MDBA) on current and projected climate impacts on the Basin's water quality. This information will shape our conceptual understanding of the relationships of flow, temperature and extreme weather patterns with water quality. The review will also enable the identification of knowledge gaps and areas where the science is contested or inconclusive.

Conceptual models: The conceptual models will be developed based on the current literature and the project team's knowledge and understanding of potential impacts of climate change on the Basin's water resources. The conceptual models will clearly outline the linkages and cause-effect relationships for surface and groundwater resources in the face of climate change, including direct and indirect impacts, such as: *temperature change (rise), changed rainfall amounts, changed rainfall patterns, changed water balance, changed vegetation and land-use.*

A workshop for specialists in water quality and climate change in the MDB. These specialists will be identified by the MDBA. Workshop will finalise conceptual models for risk assessment. Two lists of models will be developed, one consisting of models of high confidence that can be assessed to provide quantitative results and another consisting of less confidence models for which a qualitative analysis is appropriate. (NB It is unlikely that the linkages between climate change and the flow-water quality relationship in each basin will be strong enough for quantitative modelling).

Climate inputs required

- SKM will provide a synthesis of current information on the three climate change scenarios as they apply to the MDB, including projected water availability, temperature rises and rainfall patterns. (They are assuming all the information for each scenario will be well defined for each of the MDB basins. At the very least they require the direction of the trajectory of rainfall, extremes, runoff and temp for each of the climate scenarios, and each MDB basin).
- SKM will use the CSIRO (2008) model of temperature change, water availability and rainfall patterns and other available climate change modelling outputs to determine the *likelihood* of changes to water quality 'value' through their conceptual models

Other inputs required

- SKM will collect water quality data and information on water quality issues experienced through the MDB
- A possible source of landuse data and projections of future landuse could be provided by the Bureau of Rural Sciences (BRS). BRS have produced Australia-wide GIS layers of landuse,

for current (2008), and predictions for 2015 and 2030. The landuse predictions are generally derived by continuation of current landuse trends.

Outputs generated

- Literature review
- List of knowledge gaps
- Data gaps
- Types of data required to improve model robustness
- Map of MDB showing risk levels across the 18 regions for key parameters (e.g. nutrients, salinity, algal blooms, etc.)
- Risk matrix for combining likelihood and consequence for each region for each beneficial use.
- A summary of the identified risks will be provided in a general discussion for each MDB region in the draft report. This will include a geographical presentation of the risk levels across the regions for key parameters (e.g. dissolved oxygen):

	Climate Change Scenarios		
Sub region	Most favourable 2030	Medium 2030	Least favourable 2030
Avoca	Low	Medium	Medium
Border Rivers	Medium	Medium	High
Broken	Low	Low	Medium
Campaspe	Medium	Medium	High

- Recommendations for future work.

Deliverables/products

- The risk framework and developed spatial layers will be made available to the MDBA at the conclusion of the project
- Literature review
- Conceptual models (workshop outcomes)
- Risk assessments
- Gap analysis and recommendations for further work
- Interim report
- Draft report
- Final report.

Communication plan

The report will be written in a way that it can be easily communicated to water policy makers, water planners and interested industry and community groups.

Repeatability of method with new climate scenarios or new information

Risk assessment results can be updated periodically based on inclusion of new data and/or monitoring information. Further, risk-reduction strategies are developed from improved understanding of both the risks posed by specific stressors and of the processes contributing to them. In this context Ecological Risk Assessment plays an important role in best-practice natural resource management based on adaptive management principles.

Links to other risk projects

SKM will work with the other risk projects to identify and /or confirm Basin climate impacts, etc. The output from this task includes: a list of water quality issues / parameters and potential climate impacts/risk scenarios for discussion at a project workshop.

Links to other MDBA work

SKM has been awarded another synthesis report project, '*Climate Change Impacts on the Murray-Darling Basin's Salinity Dynamics and Mobilisation Processes*'.

MDBA is developing a Water Quality Strategy/Plan as part of the Basin Plan.

Links to other work outside MDBA

- Implications of Climate Change for Natural Resources Management in the Murray-Darling Basin: Part 1: A collation of recent research;
- Salinity Targets Review for Murray-Darling Basin Authority (2009);
- Murray-Darling Basin Sustainable Yields Project;
- Sustainable Rivers Audit of Murray Darling Basin Rivers – Hydrology Index (2008);
- Southern Councils Group Climate Change Risk Management and Adaptation Plan (2009);
- Community Water Grants Water Quality Risk Assessment Tool – Development and Implementation (2007/08);
- Impact of Bushfires on Water Quality in the Gippsland Lakes;
- Environmental flows assessment of the lower Loddon River under climate change;
- A risk assessment of climate change options for the Mallee CMA; and
- Murray-Darling Basin 2008 Risk Assessment Guidelines.

Appendix C Overview of MDBA climate research and review

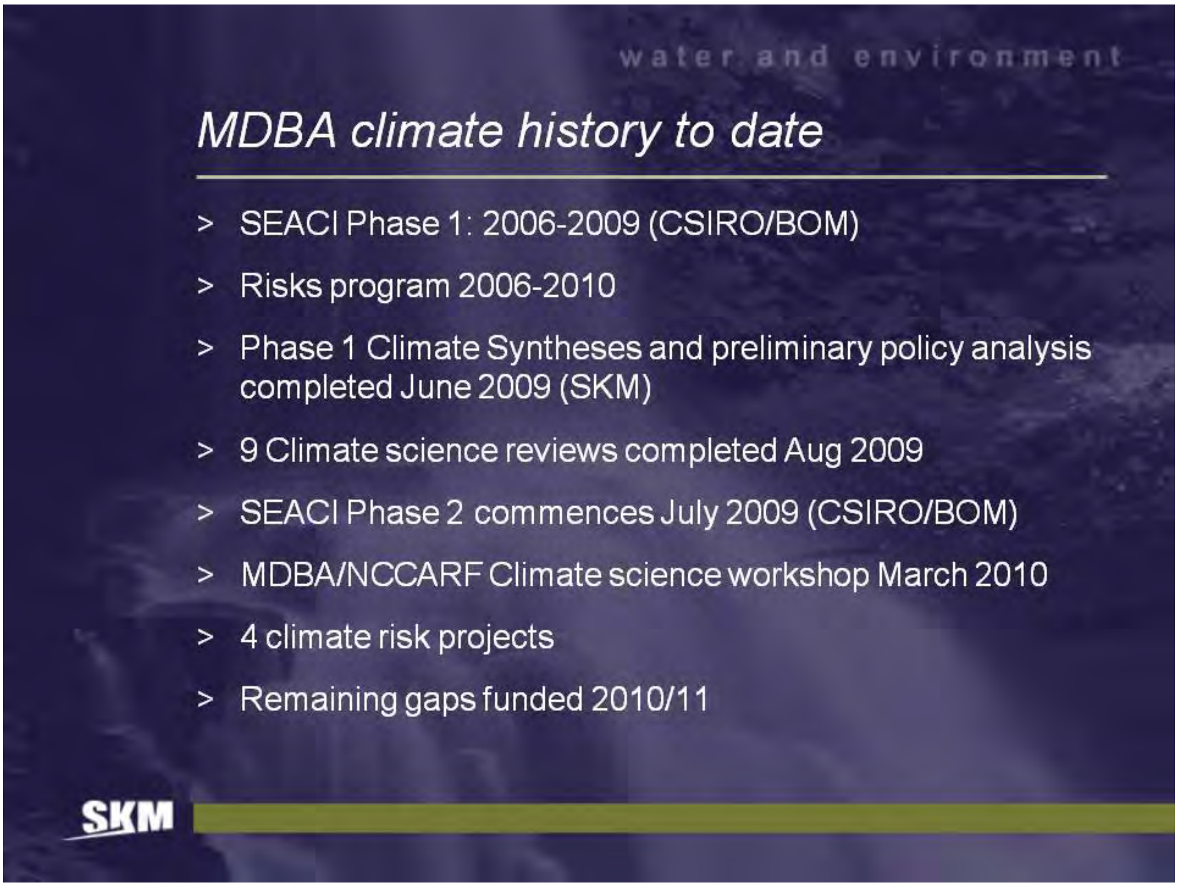
Action	Date
1. Phase 1 Syntheses (a) Implications of Climate Change for Natural Resource Management in the Murray-Darling Basin - Part 1: Collation of Recent Research (b) Implications of Climate Change for Natural Resource Management in the Murray-Darling Basin - Part 2: Policy Analysis of SEACI and Climate Science Reviews (c) Implications of Climate Change for Natural Resource Management in the Murray-Darling Basin - Part 3: Preliminary Policy Synthesis	30 June 2009
2. Science reviews *Evans, J. Pitman, A.* Scientific review of the atmospheric and land surface dynamics of the Murray-Darling Basin *Gell, P. et al* Palaeo-climate Studies relevant to NRM in the Murray-Darling Basin *Helman, P.* Drought periods in the Murray-Darling Basin since European settlement *Karoly, D.* Climate variations and causal processes *Kiem, A.* Review of current understanding into MDB climate patterns and causal processes *Low, T.* Scoping Study - significant ferals and weeds, risks, options and implications for the MDB *Procter, W.* Scoping adaptation strategies and research applicable to natural resource management in the Murray-Darling Basin – literature review *Roderick, M.* Evapotranspiration Trends and Water Availability: the Murray-Darling Basin now and into the future *Stone, R.C.* Comprehensive review into the core climate patterns, droughts, rainfall systems and associated causal processes relevant to the Murray-Darling Basin at a range of associated time scales.	June-August 2009
3. Climate science workshop *Jason Alexandra* overview of the MDB and challenges faced in the context of climate change *Graeme Pearman* South-East Australia Climate Initiative (SEACI): Phase 1 synthesis *Prof. David Karoly and Dr. Ailie Gallant* Climate patterns and causal processes of wet and dry sequences in the Murray-Darling Basin	March 2010

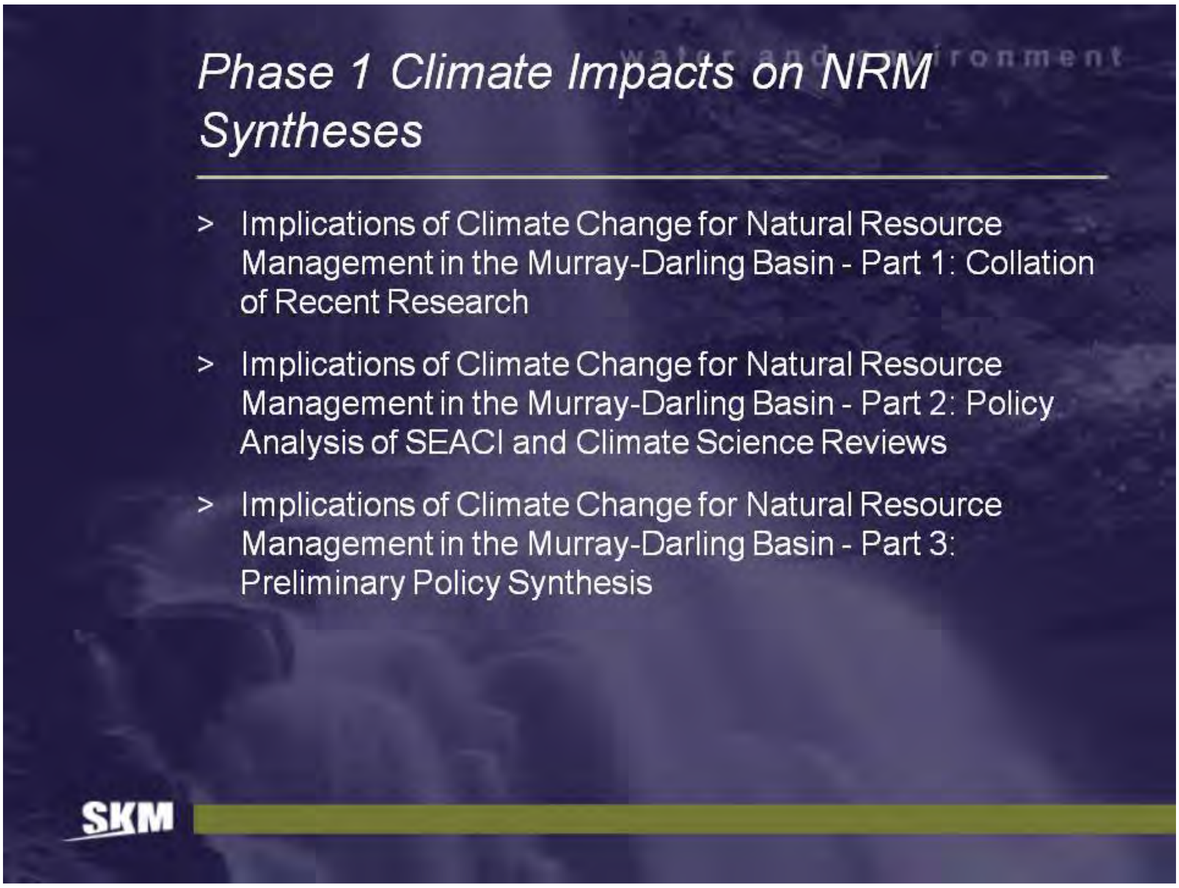
Anthony Kiem and Danielle Verdon-Kidd Current understanding into Murray-Darling Basin climate patterns and causal processes _Lu Zhang_ Assessing the Impact of Climate Change on Water Availability _Michael L. Roderick, Fubao Sun, Wee-Ho Lim, Graham D. Farquhar_ Water availability in the Murray Darling Basin _Dr Peter Helman_ Droughts in the Murray-darling Basin since European settlement _Peter Gell_ Paleoclimate Studies relevant to NRM in the MDB _Jason Evans & Andy Pitman_ Coupled atmospheric and land surface dynamics over South East Australia _Tim Low_ Weeds & Pests & Climate Change in the Murray-Darling Basin _Mark Howden, Mark Stafford Smith, Wendy Proctor, Karen Hosking and Trevor Booth_ Future research needs for climate adaptation in the MDB **Notes:** 1. Workshop notes typed up and being finalised by NJS 2. Michael Roderick facilitating WRR special issue (see attached) 3. Slides to go on NCCARF website (being organised by Alice) 4. Mathew is preparing a minute to MDBA executive on above	
4. SEACI Phase 1 Review ▪ Has been finalised and reviewed but not yet released ▪ A 2-page policy synthesis has been prepared for Minister to release	April 2010
5. Climate risk projects _Dr Fran Sheldon_ Impacts of Climate Change on the Aquatic Ecosystems of the MDB _Prof Quentin Grafton_ Impacts of Climate Change on the People, Communities and Industries of the MDB _Greg Holland_ Risk of Climate Change Impacts on Salinity Dynamics and Mobilisation Processes in the Murray-Darling Basin _Dr Bonnie Atkinson_ Impacts of Climate Change on the Murray-Darling Basin's Water Quality **Notes:** 1. Projects progressing well at this stage 2. People & industries draft review submitted – NJS to review and return comments by 23 April 3. Water Quality draft review submitted (except groundwater section) - NJS to review and return comments by 23 April 4. The question of whether the teams can use the latest MDBA climate scenarios and modelled flow data remains uncertain – Mathew attempting to resolve	March-July 2010

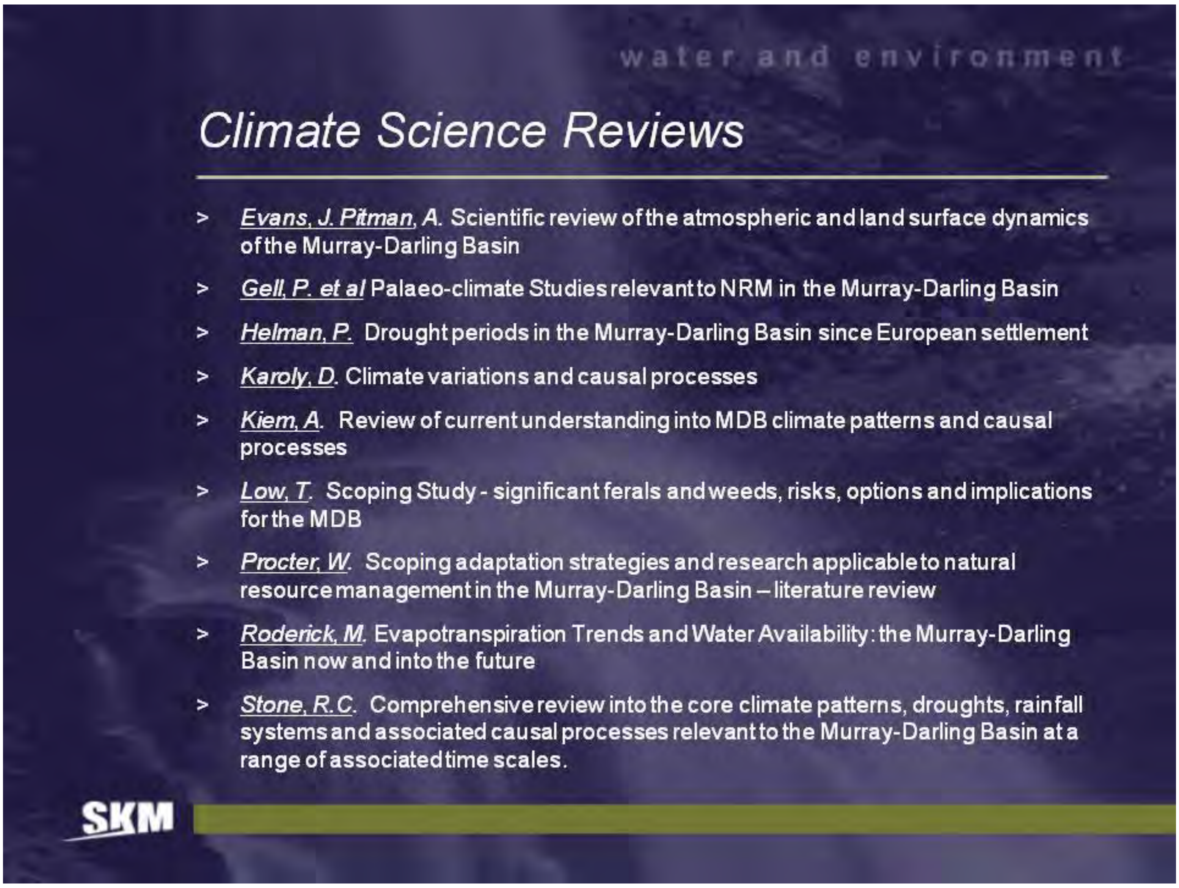
6. Other topics partially covered ▪ Bushfires (not yet funded) ▪ Native forests & woodlands (partially addressed in afforestation and forest physiology risk projects) ▪ Biodiversity (partially addressed in floodplain vegetation and terrestrial landscapes risk projects) ▪ Mitigation (currently excluded) ▪ Global climate change overview (NJS to update) ▪ Groundwater/GDEs (should be covered in Bruce Campbell's Basin Plan work?) ▪ Soil moisture (not specifically addressed) ▪ Climate impacts to date (not addressed to date but well worthwhile; a project will proceed on 'responses to the drought') **Notes:** 1. Mathew will supply list of relevant projects referred to above 2. May come back to bushfires in the future, subject to budget 3. A summary of mitigation activity in the MDB may be worthwhile for completeness 4. A thorough analysis of climate change in the MDB 1970-2009 would be well worthwhile as observational data is more reliable than predictions which are still characterised by high uncertainty. NJS to suggest approach.	June 2009
WHERE NEXT 1. Opportunity to update climate synthesis Phase 1 into a more complete Phase 2 synthesis when (5) completed. Could be several products plus communications plan. **Note:** Agree this is an important activity to start addressing now. $24m investment to date. NJS will prepare a draft communication plan as part of current project and, following discussion, potentially put into a project brief format. A 50-80 page book could be considered. 2. What else do we do with the science reviews. Reports could go on the MDBA website but need to check if would compromise WRR publication? Some would need an update (especially Kiem & Verdon). Timing awkward if wait 12 months for WRR. **Note:** Agree putting up reports would compromise WRR. Wait until WRR	

approval gained. Consider in overall communication plan. 3. Climate workshop – not much more to do once slides put on website. Many will be impossible to understand. Finish notes from workshop and see if anything in that of use? Other ideas? **Note:** suggested that a MDBA slide set with an education package could be developed as part of the communication plan 4. Would be good to see SEACI phase 1 synthesis. **Note:** will be available after Ministerial launch. It's at a fairly high level. 5. Climate risk projects finish July/August. Reviews starting to come in now – important component. **Note:** agree these reviews are important and could be peer-reviewed to add to other science reviews. 6. Other topics (6) to explore more. 7. Future research priorities should be a product.	
OTHER POINTS 1. There is a NCCARF conference end June/start July and MDBA are supporting a climate impacts/risks component. Jason will be away but would be good if NJS can support/present. 2. NWC, DCC, CSIRO expressed support for a joint project to analyse CC impacts on high yielding catchments. 3. There will be a need to synthesise all the risk program project later in 2010. 4. Risk assignment could be the big issue for the next 2 years?	


water and environment
MDBA & climate impacts
Where are we at?
28 April 2010
SKM


water and environment
MDBA climate history to date
> SEACI Phase 1: 2006-2009 (CSIRO/BOM)
> Risks program 2006-2010
> Phase 1 Climate Syntheses and preliminary policy analysis completed June 2009 (SKM)
> 9 Climate science reviews completed Aug 2009
> SEACI Phase 2 commences July 2009 (CSIRO/BOM)
> MDBA/NCCARF Climate science workshop March 2010
> 4 climate risk projects
> Remaining gaps funded 2010/11
SKM


Phase 1 Climate Impacts on NRM Syntheses
> Implications of Climate Change for Natural Resource Management in the Murray-Darling Basin - Part 1: Collation of Recent Research
> Implications of Climate Change for Natural Resource Management in the Murray-Darling Basin - Part 2: Policy Analysis of SEACI and Climate Science Reviews
> Implications of Climate Change for Natural Resource Management in the Murray-Darling Basin - Part 3: Preliminary Policy Synthesis
SKM


water and environment
Climate Science Reviews
> Evans, J. Pitman, A. Scientific review of the atmospheric and land surface dynamics of the Murray-Darling Basin
> Gell, P. et al Palaeo-climate Studies relevant to NRM in the Murray-Darling Basin
> Helman, P. Drought periods in the Murray-Darling Basin since European settlement
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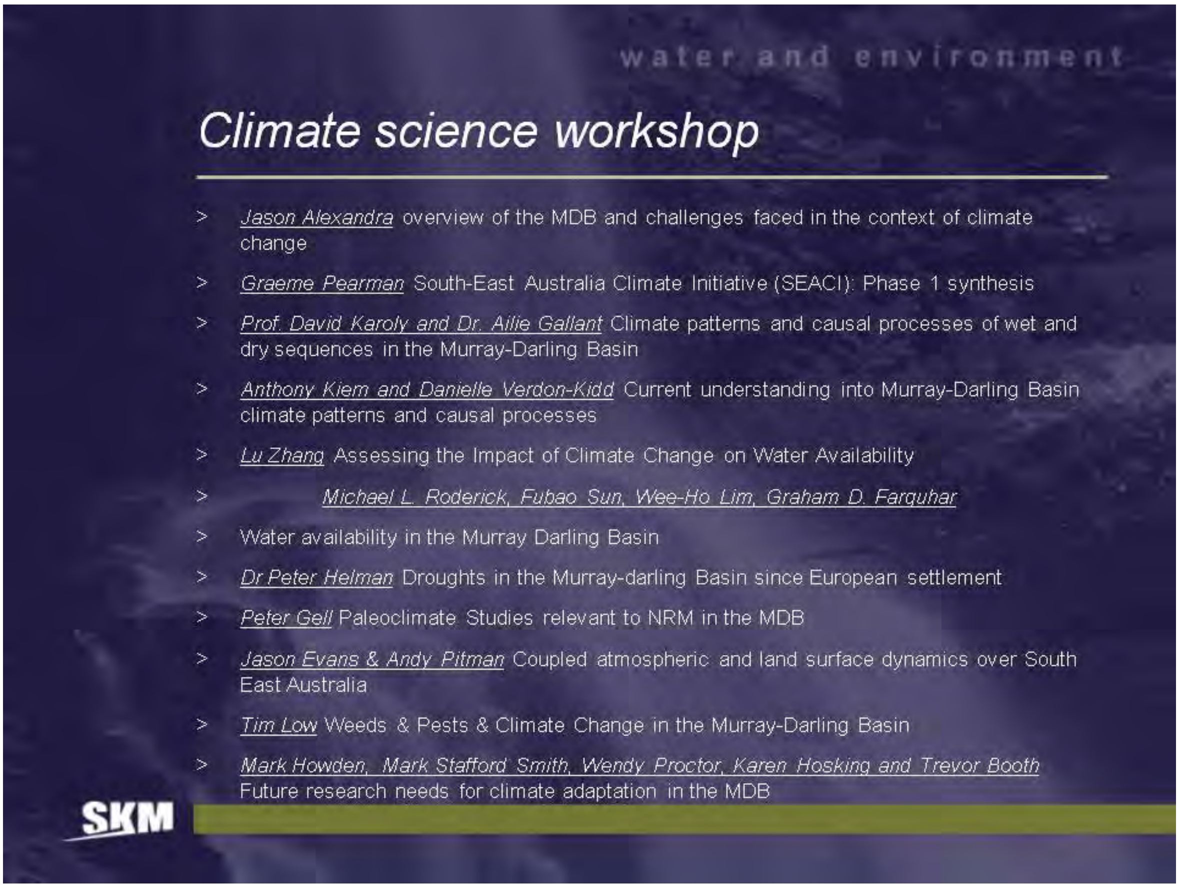
> Roderick, M. Evapotranspiration Trends and Water Availability: the Murray-Darling Basin now and into the future
> Stone, R.C. Comprehensive review into the core climate patterns, droughts, rainfall systems and associated causal processes relevant to the Murray-Darling Basin at a range of associated time scales.
SKM


water and environment
Climate science workshop
Jason Alexandra overview of the MDB and challenges faced in the context of climate change
Graeme Pearman South-East Australia Climate Initiative (SEACI): Phase 1 synthesis
Prof. David Karoly and Dr. Ailie Gallant Climate patterns and causal processes of wet and dry sequences in the Murray-Darling Basin
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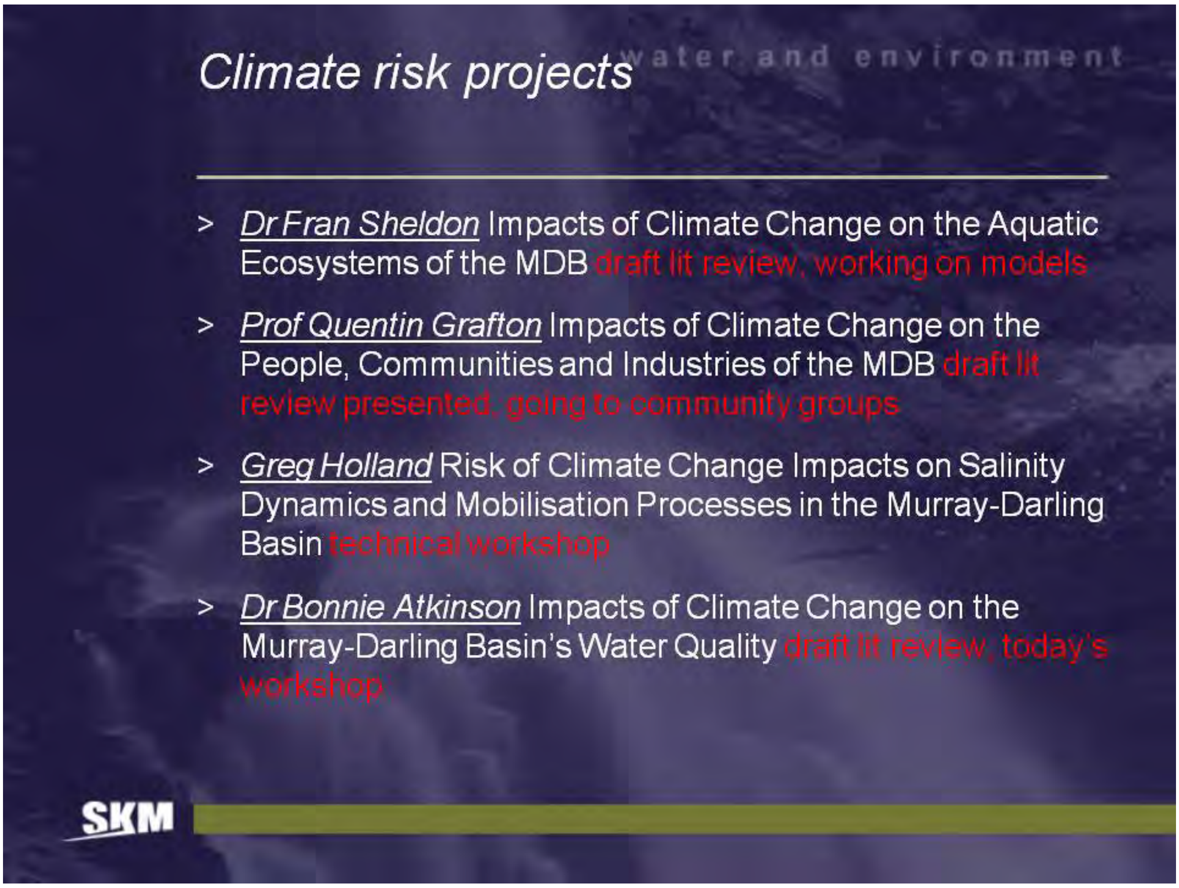
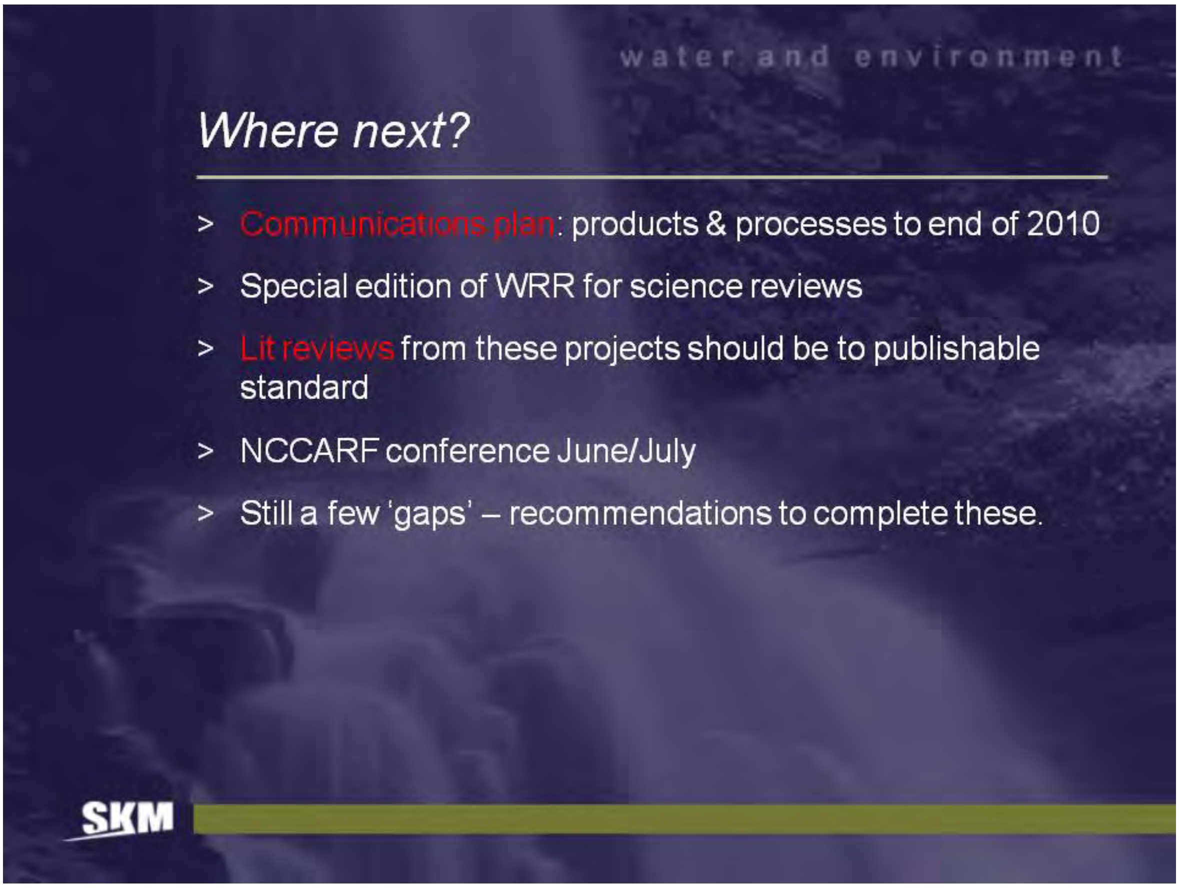
Mark Howden, Mark Stafford Smith, Wendy Proctor, Karen Hosking and Trevor Booth Future research needs for climate adaptation in the MDB
SKM


SEACI Phase 1 Review
water and environment
> Has been finalised and reviewed but not yet released
> A 2-page policy synthesis has been prepared for Minister to release
SKM


Climate risk projects
water and environment
> Dr Fran Sheldon Impacts of Climate Change on the Aquatic Ecosystems of the MDB draft lit review, working on models
> Prof Quentin Grafton Impacts of Climate Change on the People, Communities and Industries of the MDB draft lit review presented, going to community groups
> Greg Holland Risk of Climate Change Impacts on Salinity Dynamics and Mobilisation Processes in the Murray-Darling Basin technical workshop
> Dr Bonnie Atkinson Impacts of Climate Change on the Murray-Darling Basin's Water Quality draft lit review, today's workshop
SKM


water and environment
Where next?
> Communications plan: products & processes to end of 2010
> Special edition of WRR for science reviews
> Lit reviews from these projects should be to publishable standard
> NCCARF conference June/July
> Still a few 'gaps' – recommendations to complete these.
SKM

water and environment

Some climate change features

Feature	Effect	Feature	Effect	Feature	Effect	Feature	Effect
Greenhouse gases	CO2 fertilisation	Snowfall	Area decline	Droughts	Rainfall characteristics change	Ground water	Reduced recharge
Temperature	Increasing mean temperature	Incident radiation	Net radiation increase	Wet sequences	Frequency, duration or intensity increase		Reduced discharge
	Changing max/min temperatures		UV increase	Aerosols / Dust / VOCs			Lower water tables
	Changing frosts	Humidity	Vapour pressure deficit increase	Soil moisture	Drier soil profile	Streamflow	Less runoff
	Heat waves		Relative humidity decrease		Drier spatial extent		Less catchment yield
Rainfall	Increase/ decrease amount	Wind	Wind run		Drier seasons		Altered flow regime
	Rain - seasonal changes		Wind gusts	Evaporation	Higher potential evapotranspiration		Reduced minimum flows
	Rainfall intensity	Droughts	Frequency increase		Higher potential for canopy/understorey/litter interception		Larger flood magnitude
	Rainfall – storms, cyclones		Intensity increase		Higher potential for evaporation from soil profile		Reduced flood frequency
	Hail storms		Duration increase		Higher potential for evaporation from artificial storages	Land use change	Clearing of native vegetation feedback on climate
Snowfall	Amount decline		Spatial coverage increase		Higher potential for evaporation from natural water surfaces	Irrigation areas	Reduced evaporative surfaces

Appendix D Summary of Current Understanding of Climate Change in the MDB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What's with the climate?
A 'brief' summary of climate change knowledge in the MDB
16 May 2010
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Climate scenarios and risk assessment

i. The issues
ii. Observations
iii. Causes
iv. Predictions
v. Approaches

Some of the Issues

a. Policy makers & planners want to plan for 'full range' of potential impacts
b. Future climate projections for the MDB are highly uncertain and little more than guesswork for some parameters
c. It is difficult to separate some climate change impacts from climate variability impacts
d. There are many climate change attributes to consider
e. Changes to the 'climate system' are complex, with many interactions and feedbacks

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Some climate change features

Feature	Effect	Feature	Effect	Feature	Effect	Feature	Effect
Greenhouse gases	CO2 fertilisation	Snowfall	Area decline	Droughts	Rainfall characteristics change	Ground water	Reduced recharge
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Snowfall	Amount decline		Spatial coverage increase		Higher potential for evaporation from natural water surfaces	Irrigation areas	Reduced evaporative surfaces


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1. Observations
Global observations
Australia observations
MDB observations
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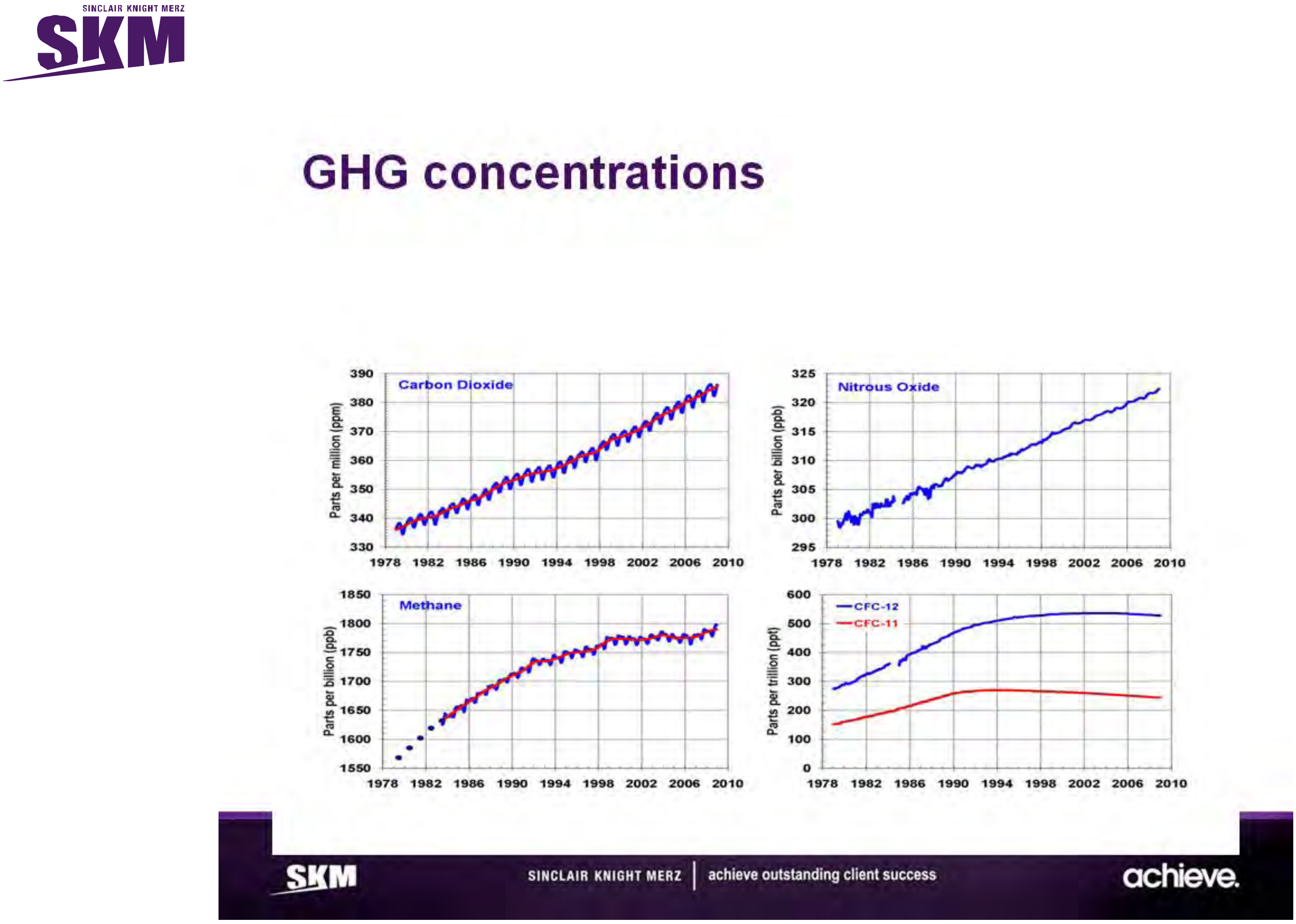
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GHG concentrations
Carbon Dioxide
Parts per million (ppm)
390
380
370
360
350
340
330
1978 1982 1986 1990 1994 1998 2002 2006 2010
Nitrous Oxide
Parts per billion (ppb)
325
320
315
310
305
300
295
1978 1982 1986 1990 1994 1998 2002 2006 2010
Methane
Parts per billion (ppb)
1850
1800
1750
1700
1650
1600
1550
1978 1982 1986 1990 1994 1998 2002 2006 2010
CFC-12
CFC-11
Parts per trillion (ppt)
600
500
400
300
200
100
0
1978 1982 1986 1990 1994 1998 2002 2006 2010
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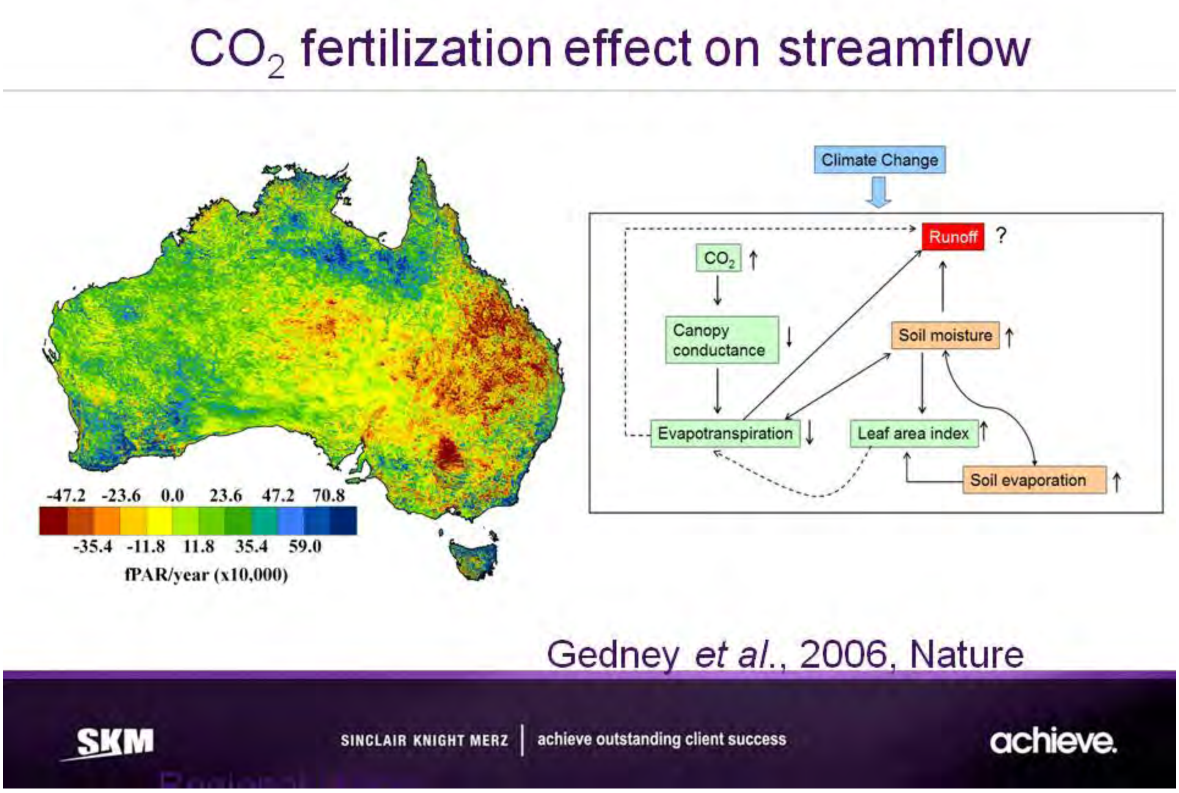

CO2 fertilization effect on streamflow
-47.2 -23.6 0.0 23.6 47.2 70.8
-35.4 -11.8 11.8 35.4 59.0
fPAR/year (x10,000)
Climate Change
Runoff ?
CO2
Canopy conductance
Soil moisture
Evapotranspiration
Leaf area index
Soil evaporation
Gedney et al., 2006, Nature
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Key points

GHGs have some direct impacts to be considered:

- ➔ CO2 fertilisation
- ➔ CO2 acidification
- ➔ streamflow

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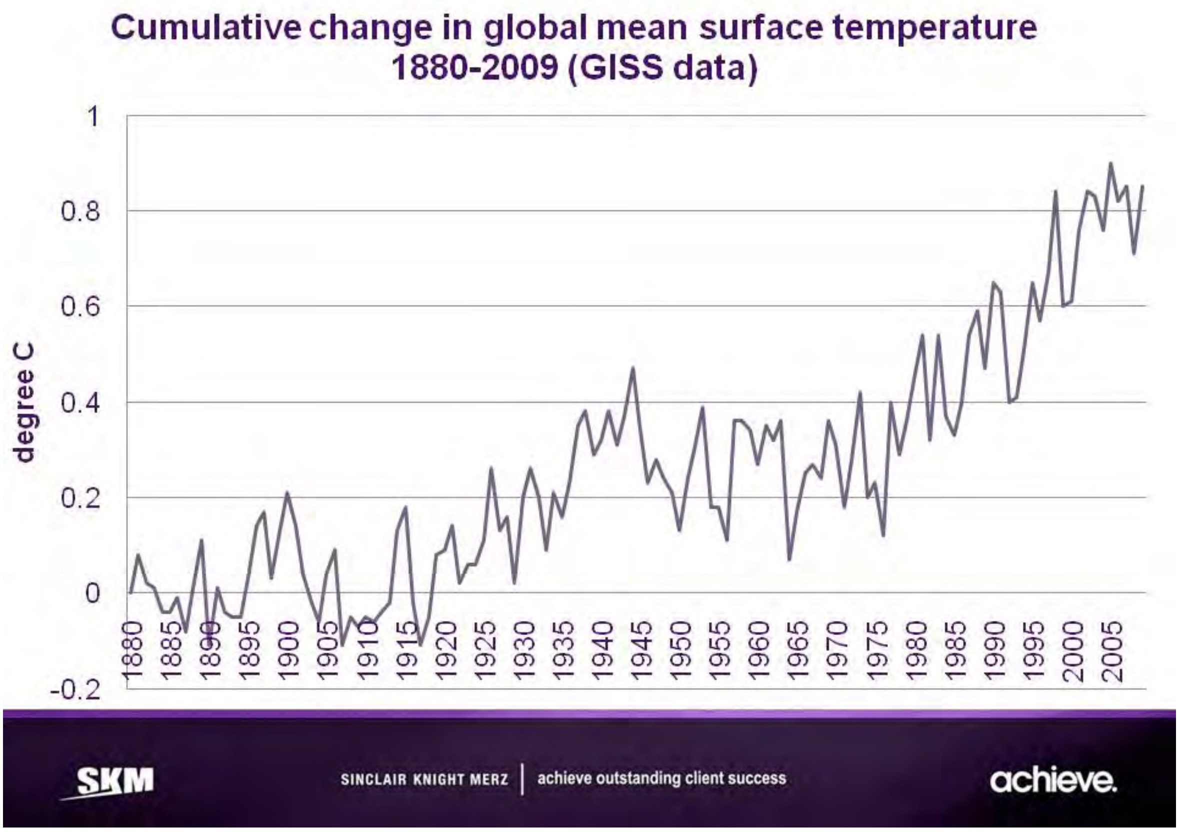
Cumulative change in global mean surface temperature
1880-2009 (GISS data)
degree C
1
0.8
0.6
0.4
0.2
0
-0.2
1880
1885
1890
1895
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
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1975
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1995
2000
2005
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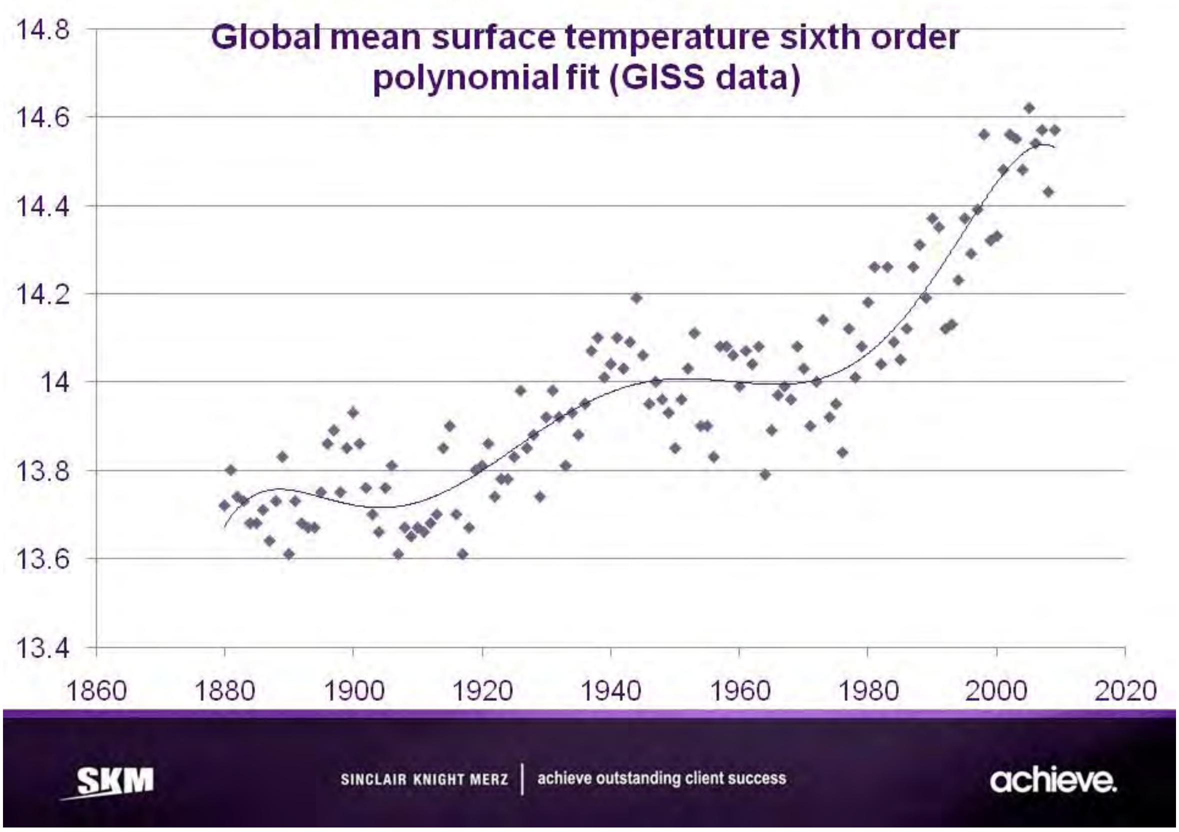

Global mean surface temperature sixth order polynomial fit (GISS data)
14.8
14.6
14.4
14.2
14
13.8
13.6
13.4
1860
1880
1900
1920
1940
1960
1980
2000
2020
SKM
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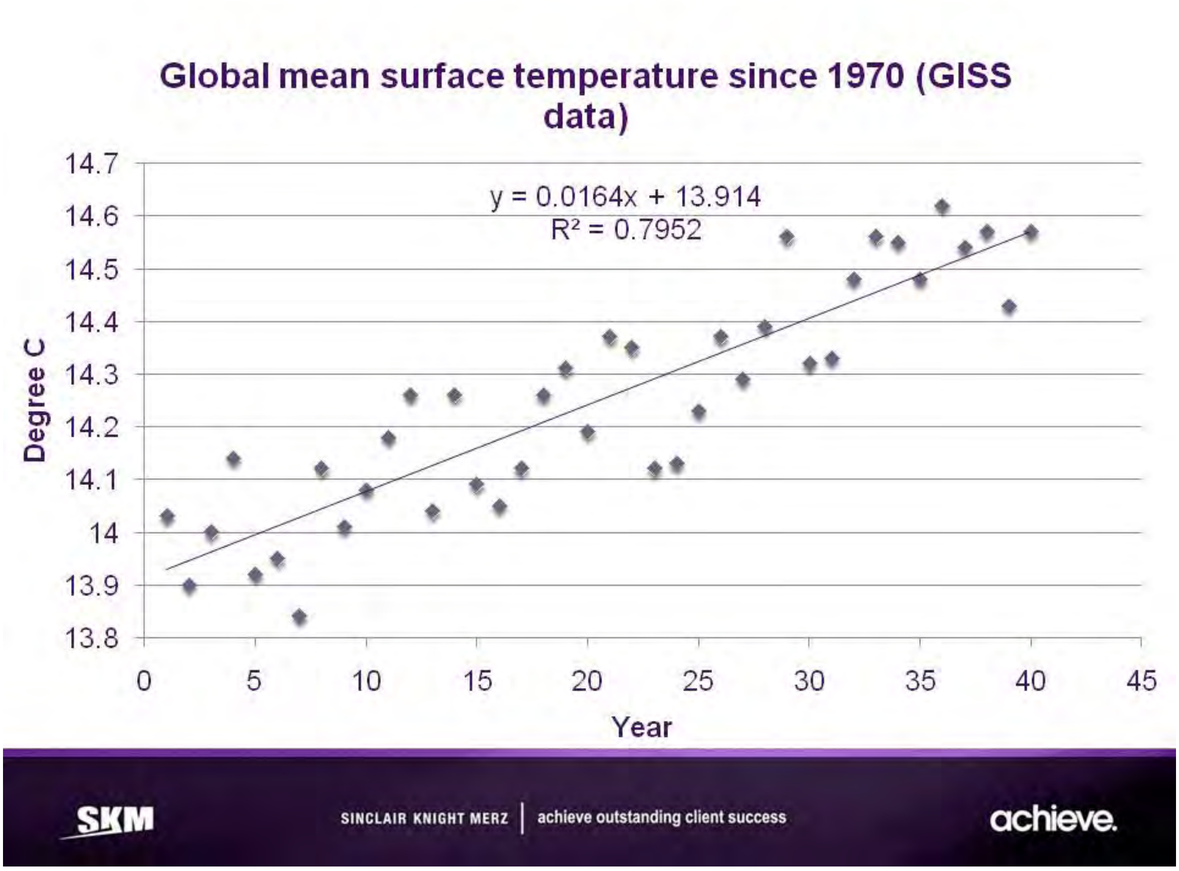
Global mean surface temperature since 1970 (GISS data)
y = 0.0164x + 13.914
R² = 0.7952
Degree C
14.7
14.6
14.5
14.4
14.3
14.2
14.1
14
13.9
13.8
0
5
10
15
20
25
30
35
40
45
Year
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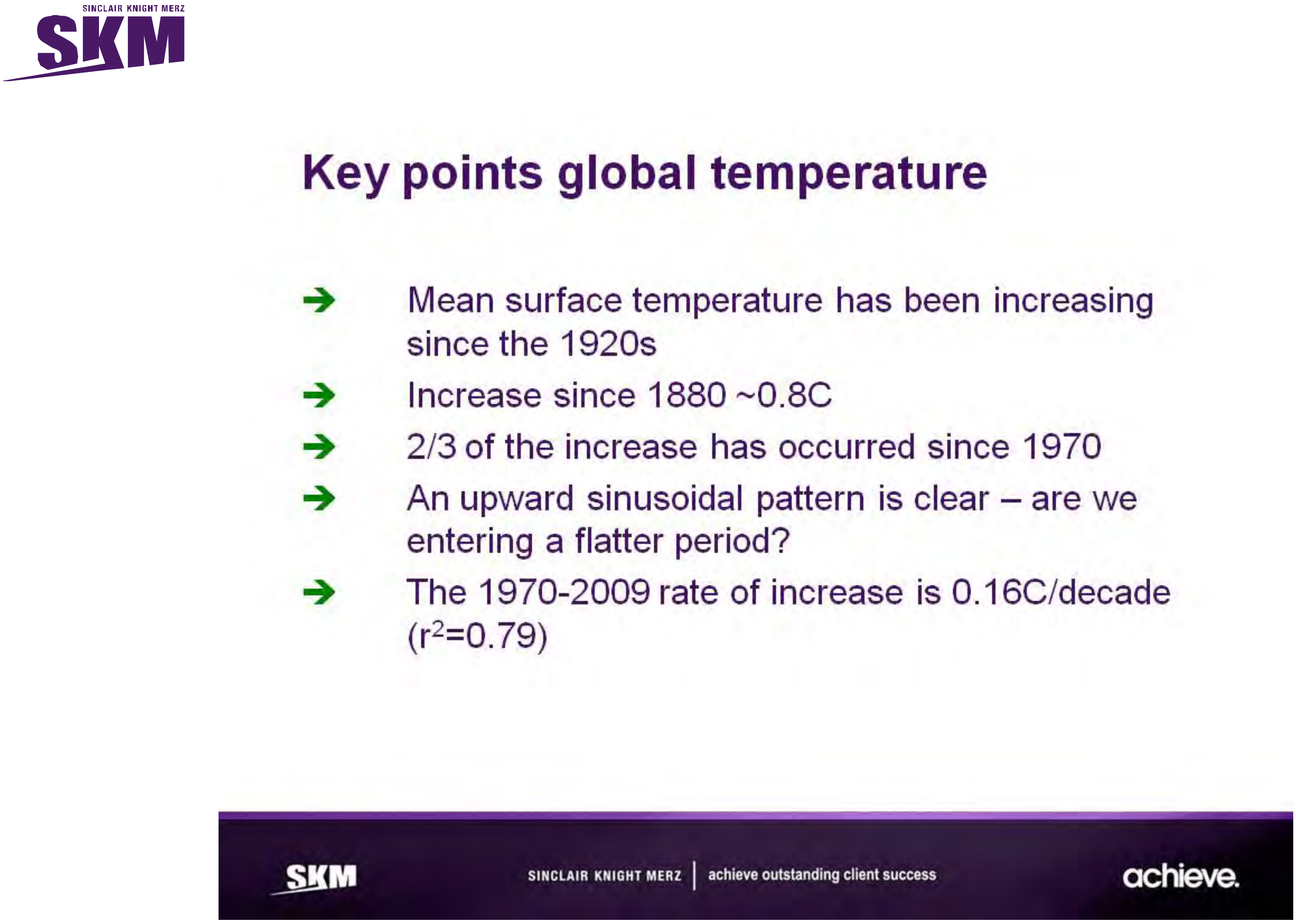
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Key points global temperature
Mean surface temperature has been increasing since the 1920s
Increase since 1880 ~0.8C
2/3 of the increase has occurred since 1970
An upward sinusoidal pattern is clear – are we entering a flatter period?
The 1970-2009 rate of increase is 0.16C/decade (r^2=0.79)
SKM
SINCLAIR KNIGHT MERZ
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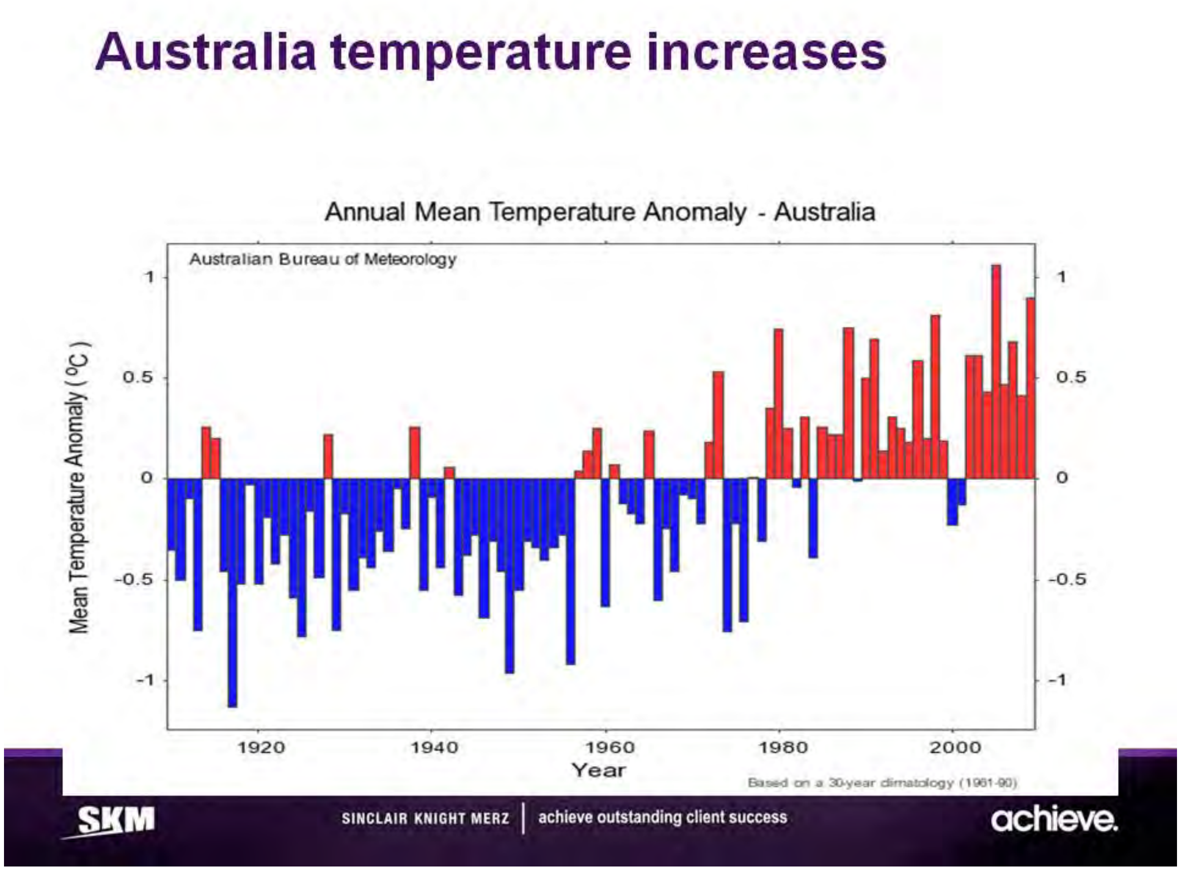
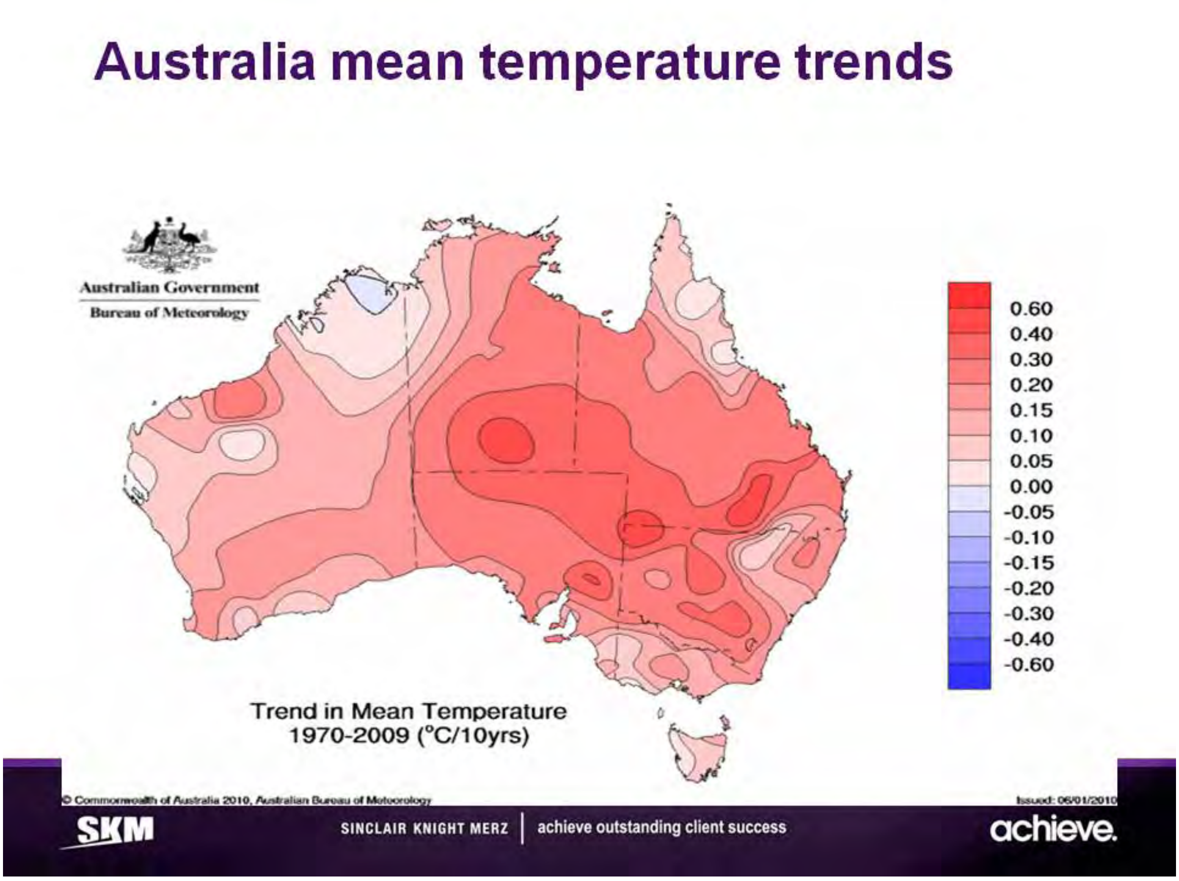
achieve.


Australia temperature increases
Annual Mean Temperature Anomaly - Australia
Australian Bureau of Meteorology
Mean Temperature Anomaly (°C)
1
0.5
0
-0.5
-1
1920
1940
1960
1980
2000
Year
Based on a 30-year climatology (1961-90)
SKM
SINCLAIR KNIGHT MERZ
achieve outstanding client success
achieve.


Australia mean temperature trends
Australian Government
Bureau of Meteorology
0.60
0.40
0.30
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.30
-0.40
-0.60
Trend in Mean Temperature
1970-2009 (°C/10yrs)
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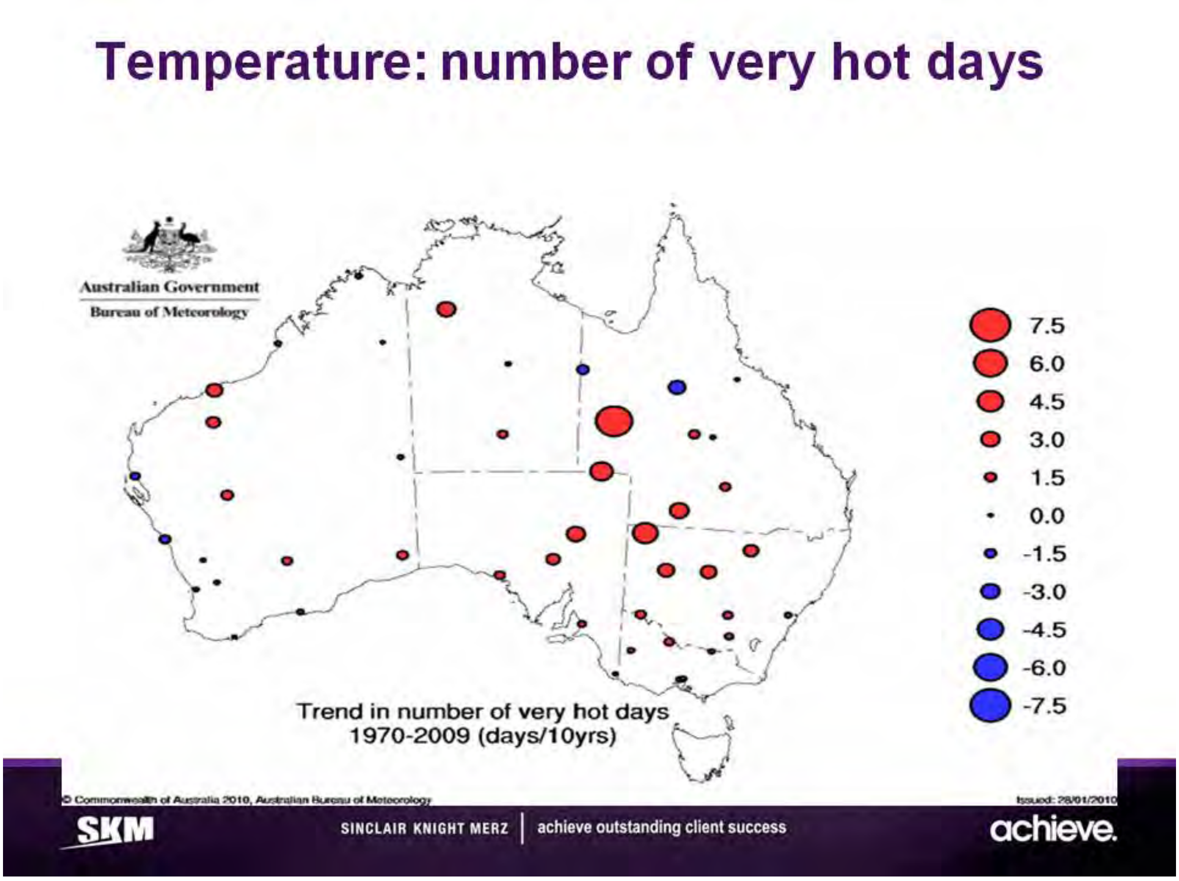
Temperature: number of very hot days
Australian Government
Bureau of Meteorology
7.5
6.0
4.5
3.0
1.5
0.0
-1.5
-3.0
-4.5
-6.0
-7.5
Trend in number of very hot days
1970-2009 (days/10yrs)
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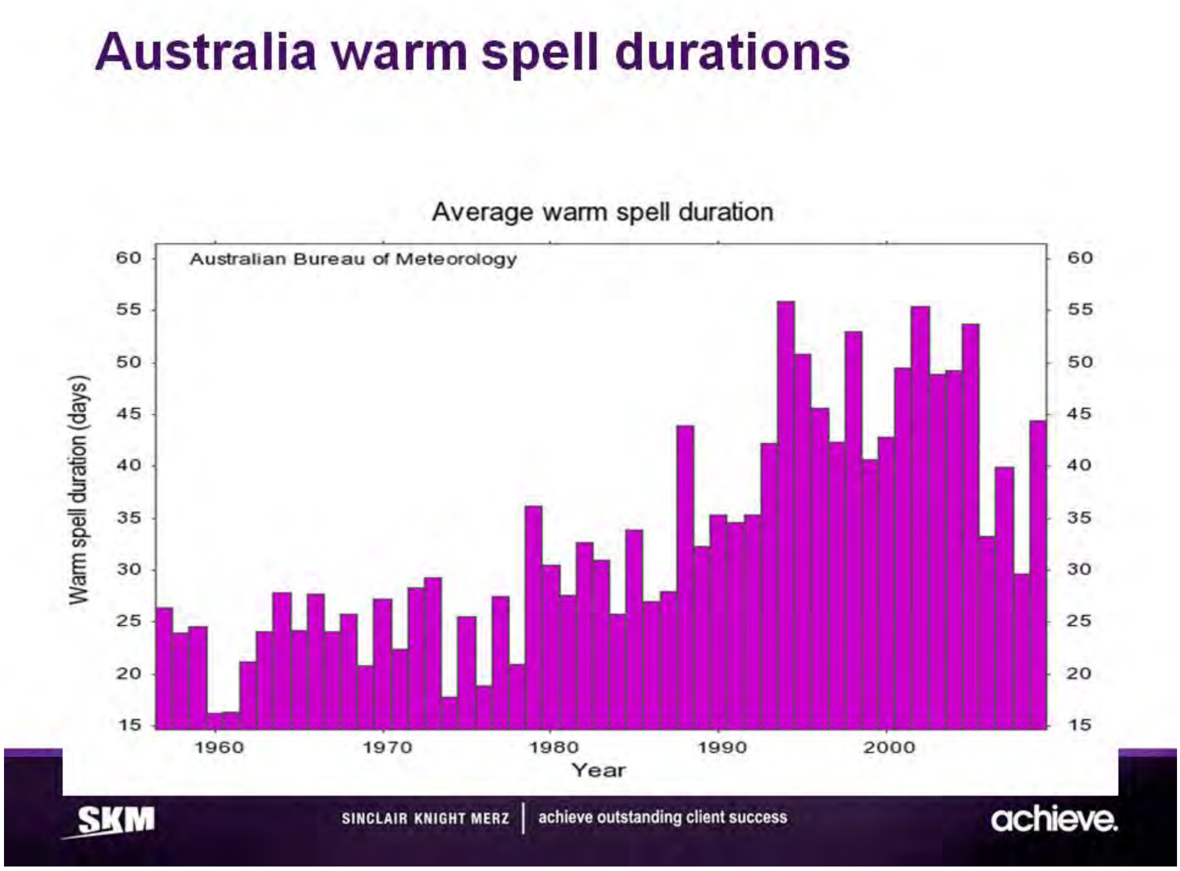
Australia warm spell durations
Average warm spell duration
Australian Bureau of Meteorology
Warm spell duration (days)
15
20
25
30
35
40
45
50
55
60
1960
1970
1980
1990
2000
Year
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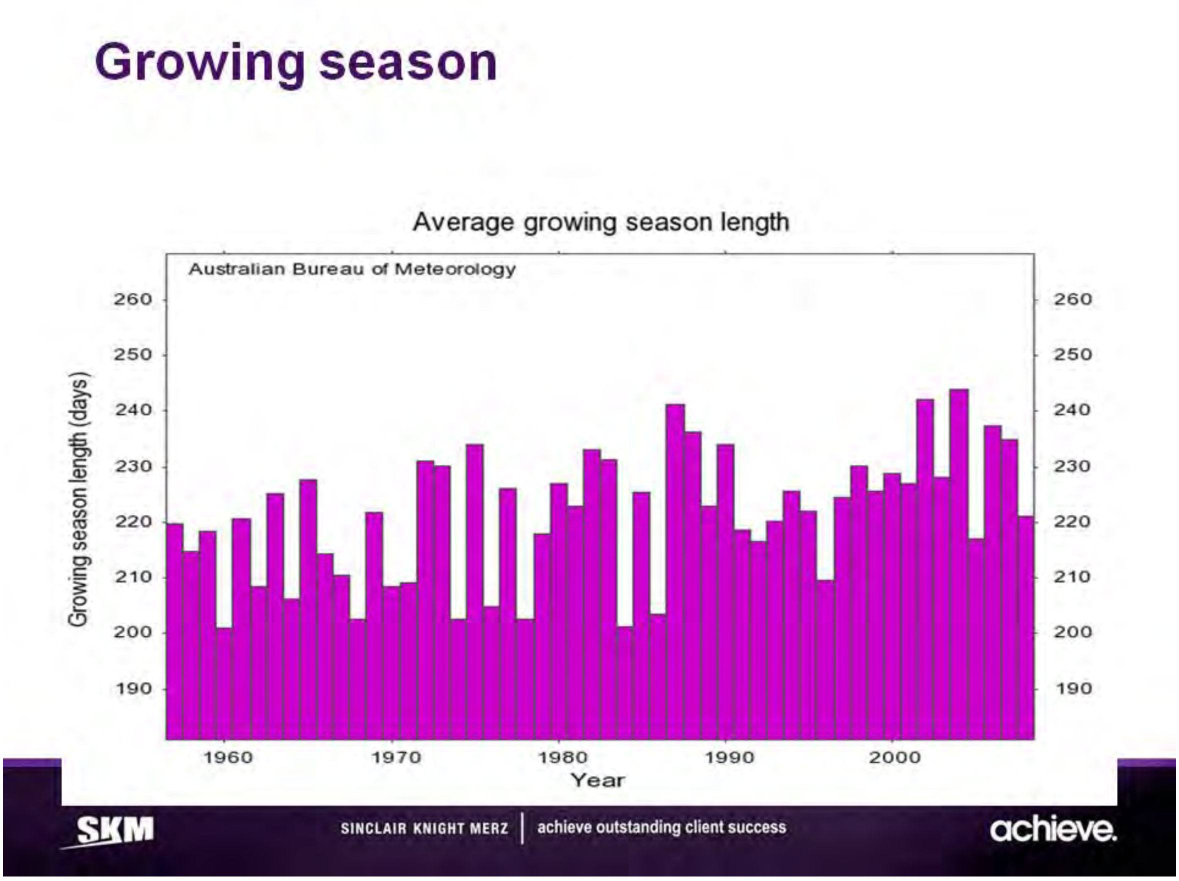
Growing season
Average growing season length
Australian Bureau of Meteorology
Growing season length (days)
190
200
210
220
230
240
250
260
1960
1970
1980
1990
2000
Year
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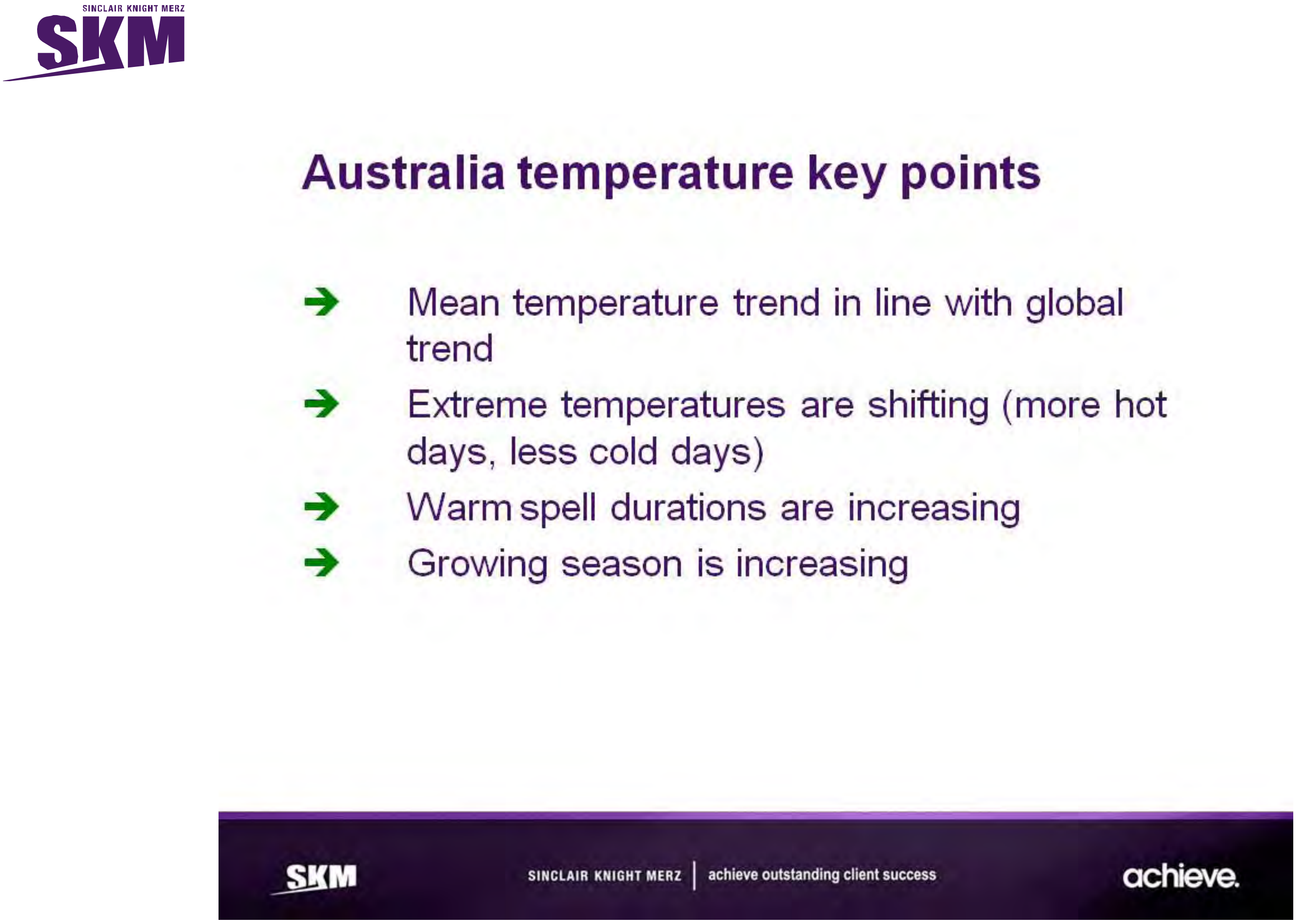
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Australia temperature key points
Mean temperature trend in line with global trend
Extreme temperatures are shifting (more hot days, less cold days)
Warm spell durations are increasing
Growing season is increasing
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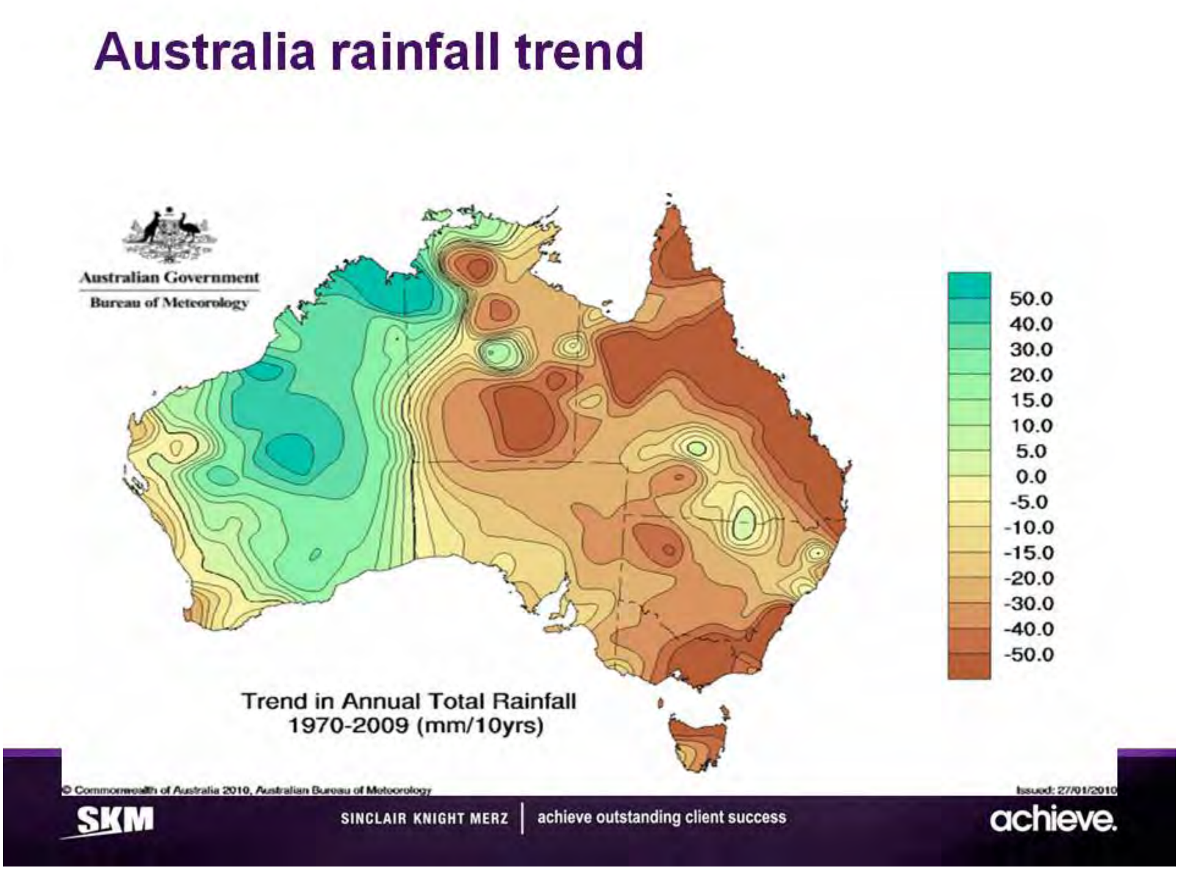

Australia rainfall trend
Australian Government
Bureau of Meteorology
50.0
40.0
30.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-30.0
-40.0
-50.0
Trend in Annual Total Rainfall
1970-2009 (mm/10yrs)
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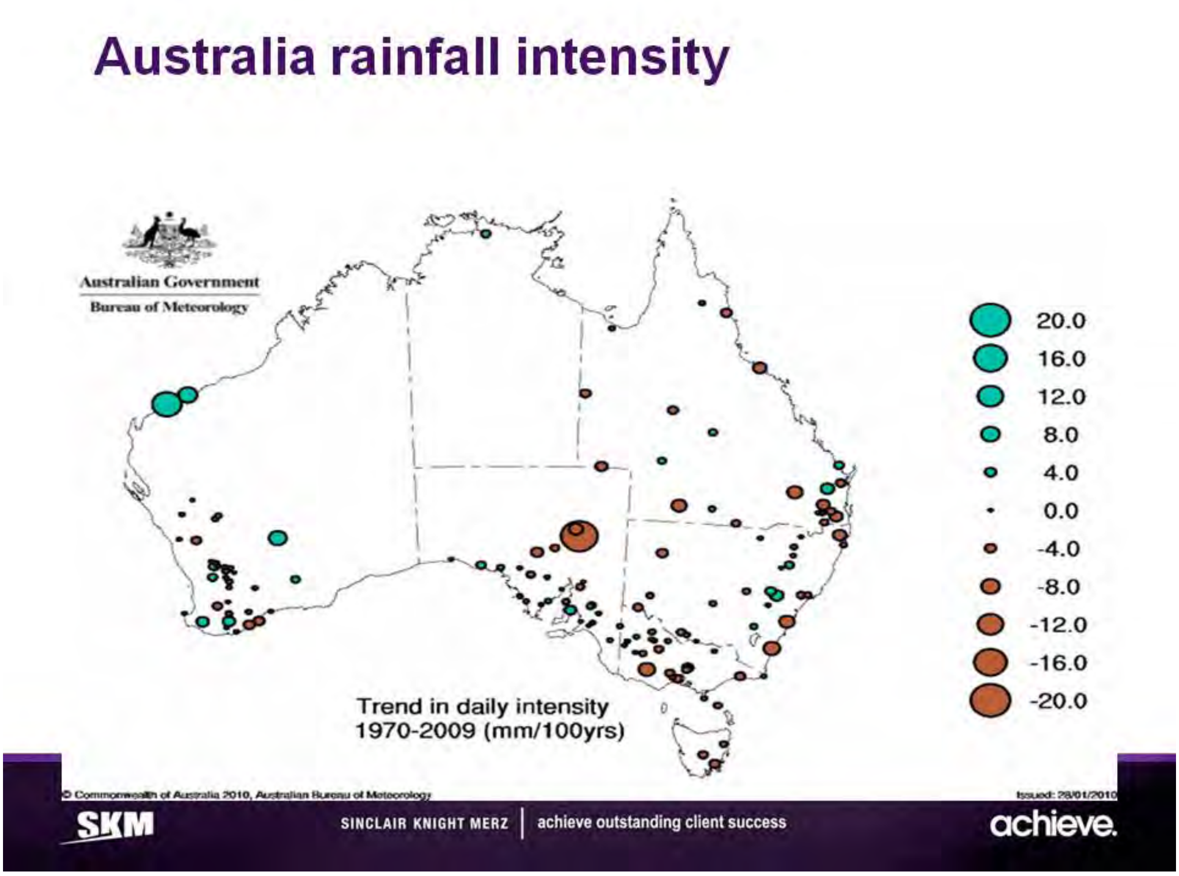

Australia rainfall intensity
Australian Government
Bureau of Meteorology
20.0
16.0
12.0
8.0
4.0
0.0
-4.0
-8.0
-12.0
-16.0
-20.0
Trend in daily intensity
1970-2009 (mm/100yrs)
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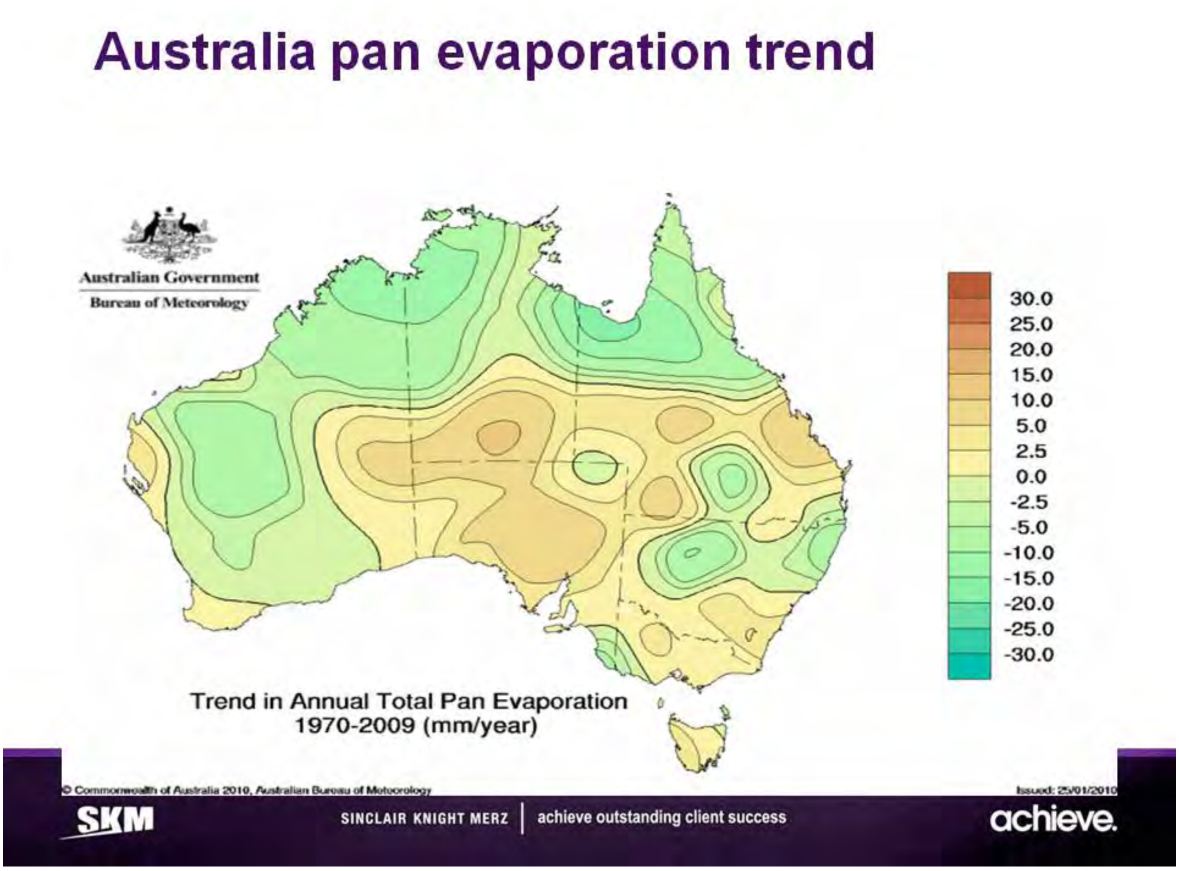
Australia pan evaporation trend
Australian Government
Bureau of Meteorology
30.0
25.0
20.0
15.0
10.0
5.0
2.5
0.0
-2.5
-5.0
-10.0
-15.0
-20.0
-25.0
-30.0
Trend in Annual Total Pan Evaporation
1970-2009 (mm/year)
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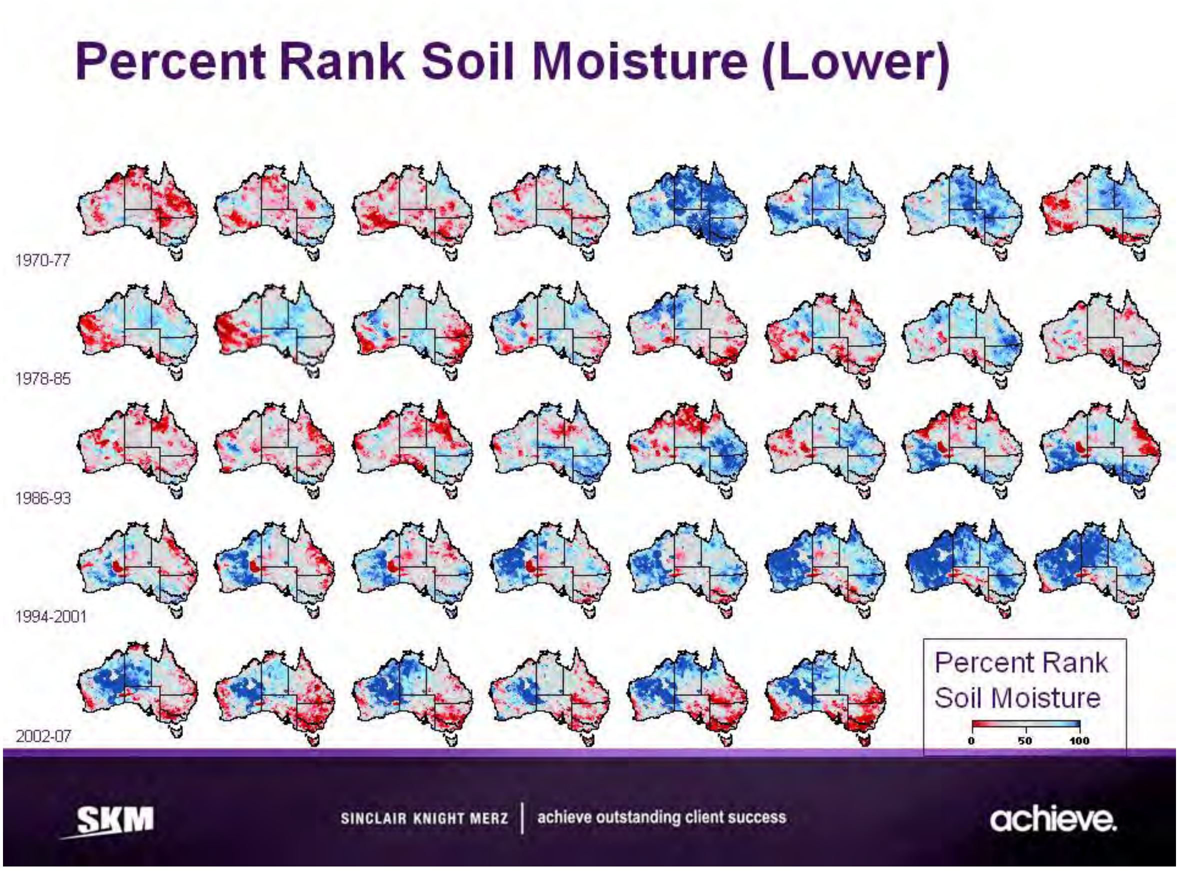
Percent Rank Soil Moisture (Lower)
1970-77
1978-85
1986-93
1994-2001
2002-07
Percent Rank
Soil Moisture
0
50
100
SKM
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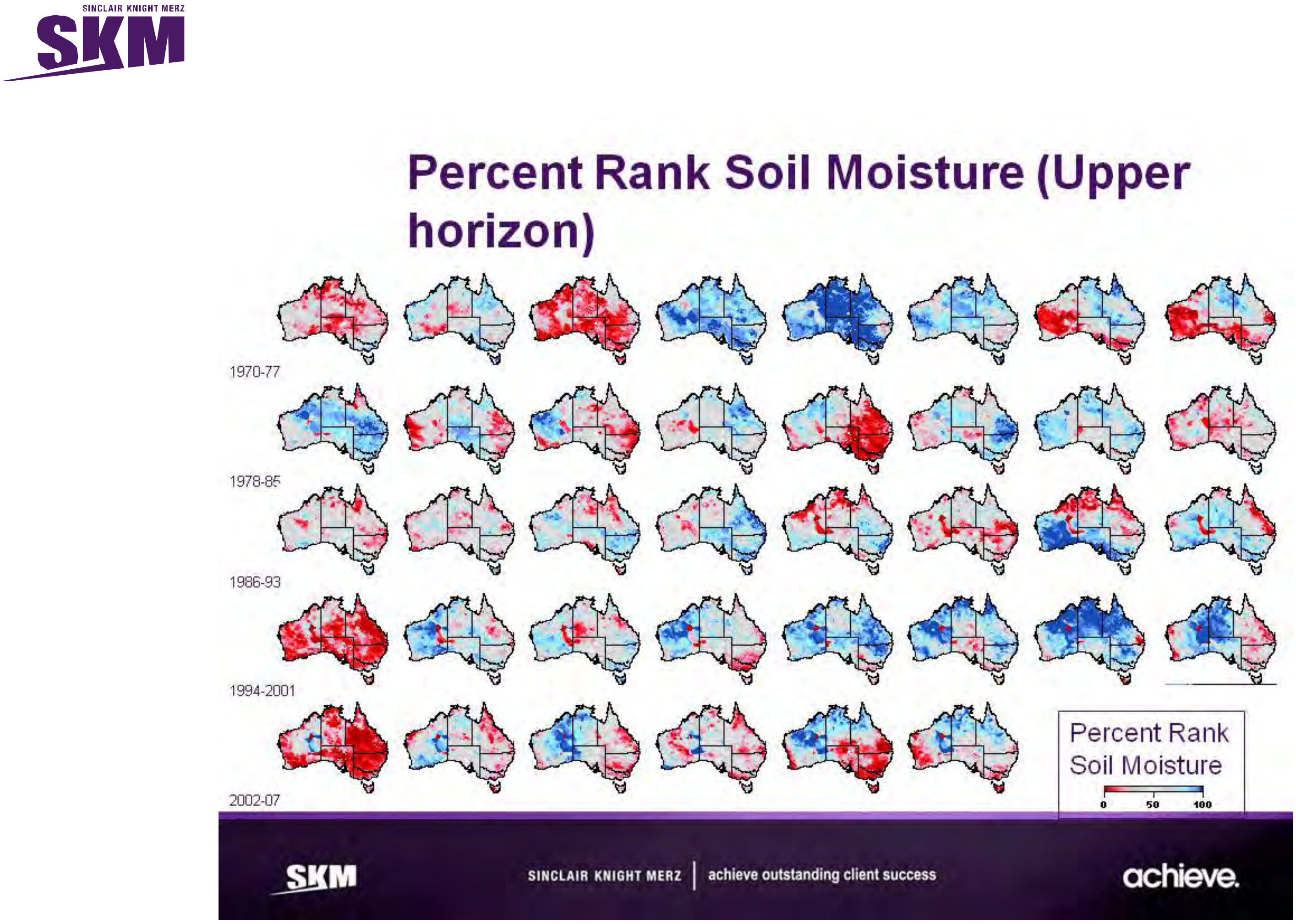
SINCLAIR KNIGHT MERZ
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Percent Rank Soil Moisture (Upper horizon)
1970-77
1978-85
1986-93
1994-2001
2002-07
Percent Rank
Soil Moisture
0
50
100
SKM
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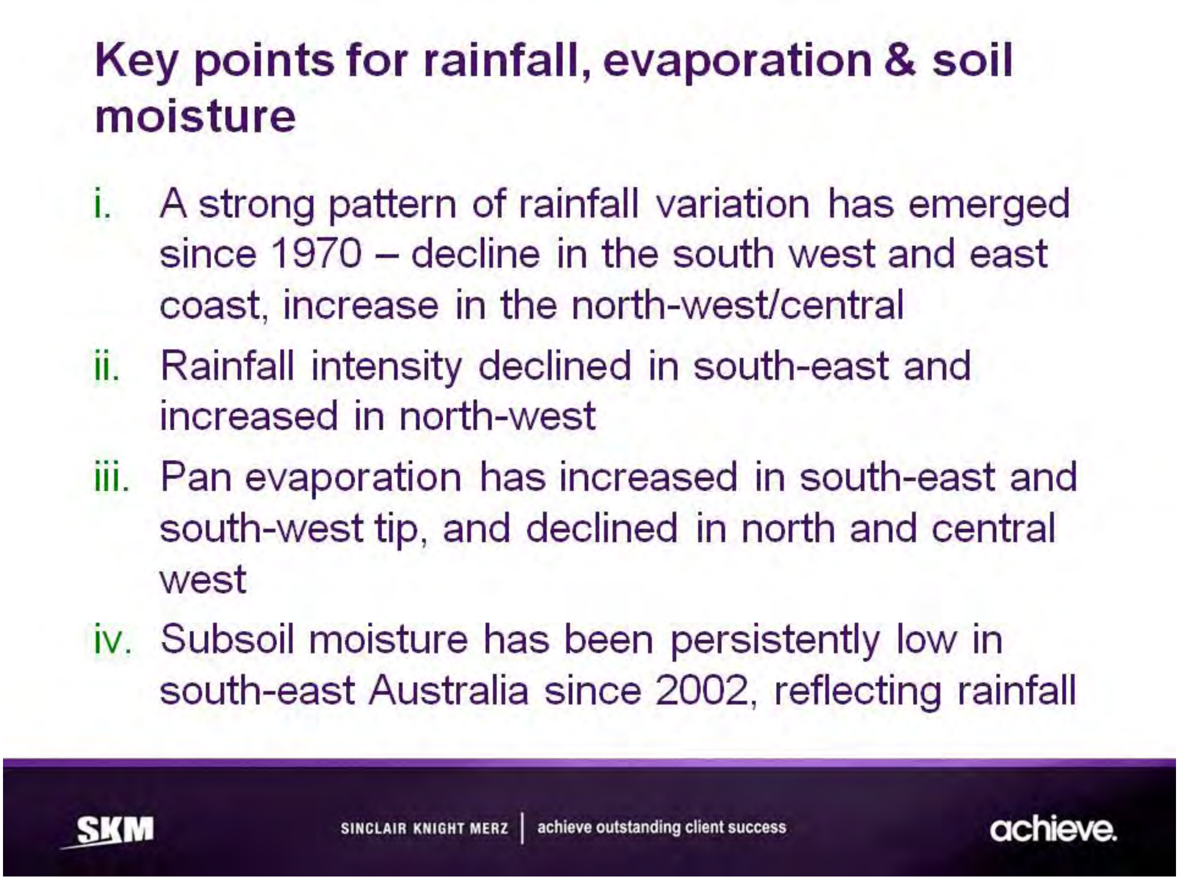
Key points for rainfall, evaporation & soil moisture
i. A strong pattern of rainfall variation has emerged since 1970 – decline in the south west and east coast, increase in the north-west/central
ii. Rainfall intensity declined in south-east and increased in north-west
iii. Pan evaporation has increased in south-east and south-west tip, and declined in north and central west
iv. Subsoil moisture has been persistently low in south-east Australia since 2002, reflecting rainfall
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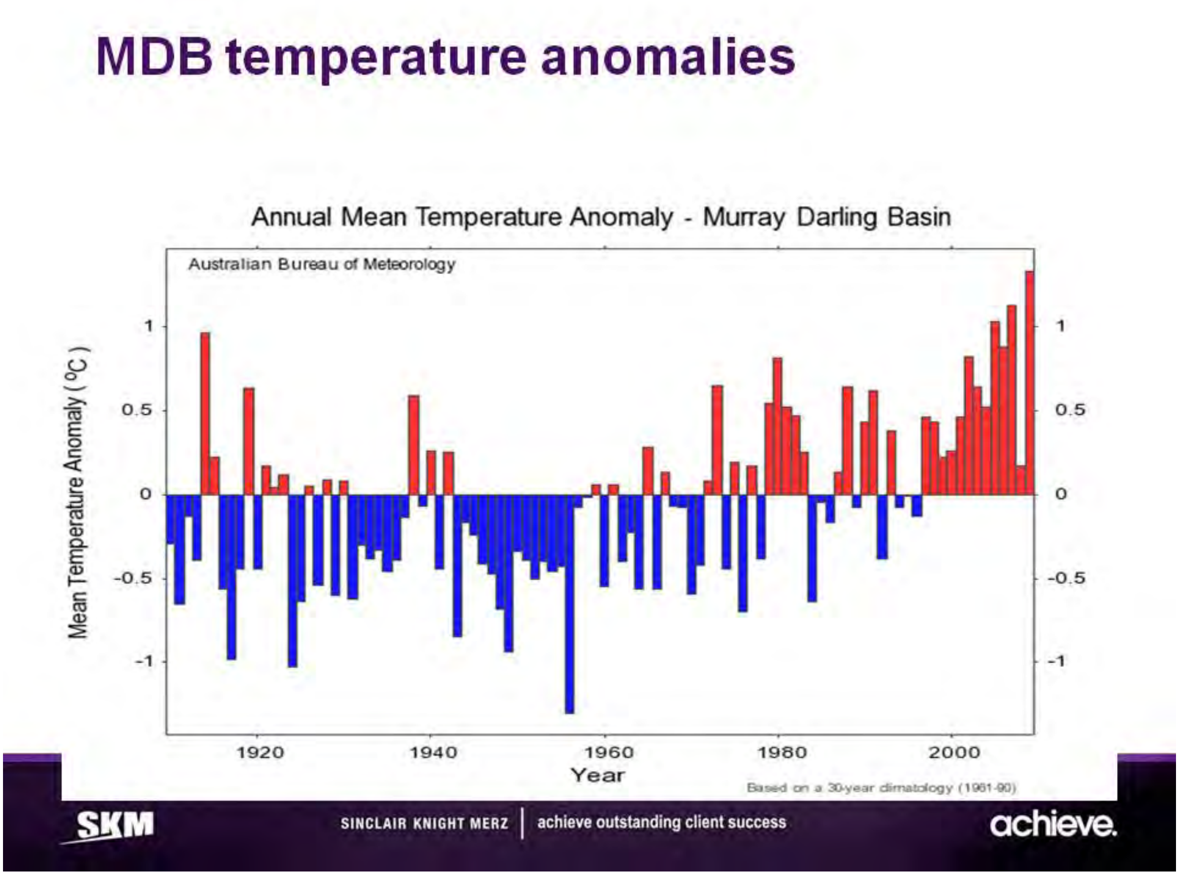
MDB temperature anomalies
Annual Mean Temperature Anomaly - Murray Darling Basin
Australian Bureau of Meteorology
Mean Temperature Anomaly (°C)
1
0.5
0
-0.5
-1
1920
1940
1960
1980
2000
Year
Based on a 30-year climatology (1961-90)
SKM
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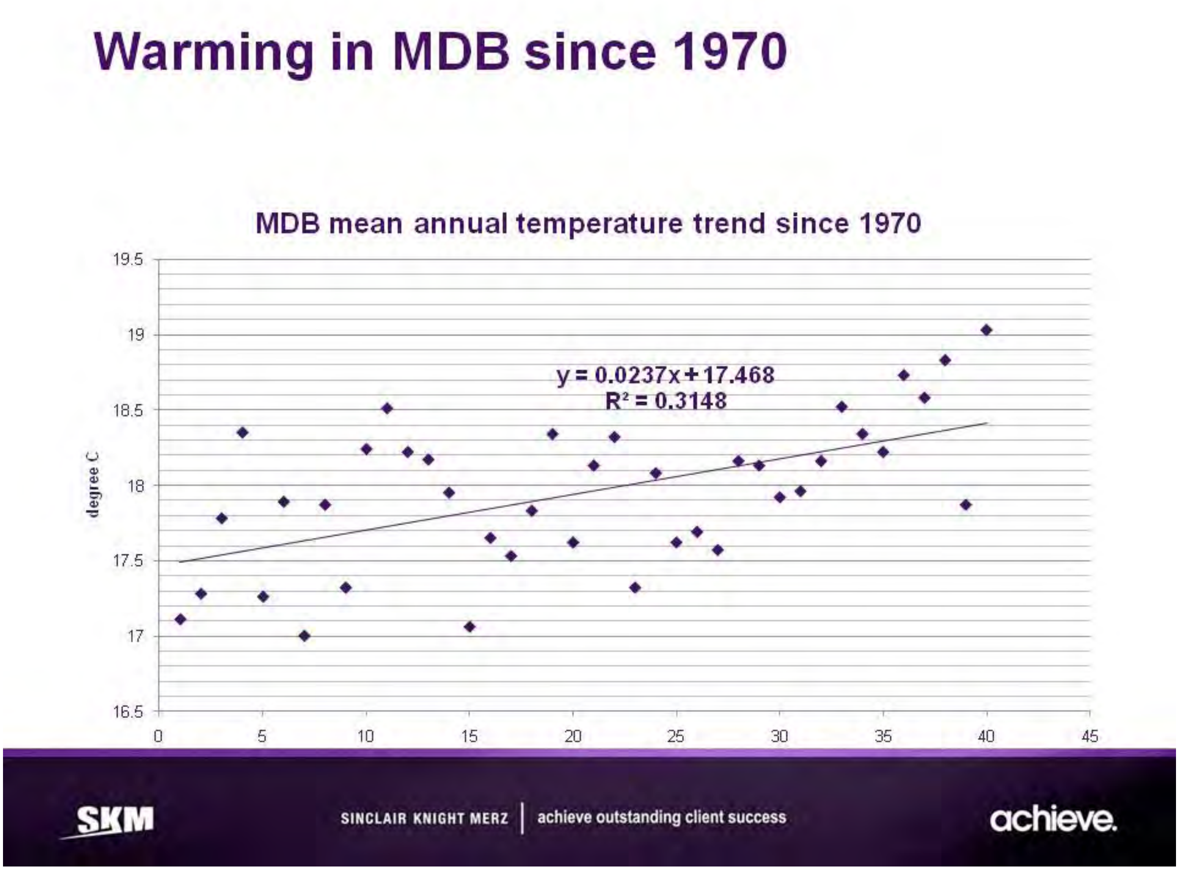
Warming in MDB since 1970
MDB mean annual temperature trend since 1970
y = 0.0237x + 17.468
R² = 0.3148
degree C
19.5
19
18.5
18
17.5
17
16.5
0
5
10
15
20
25
30
35
40
45
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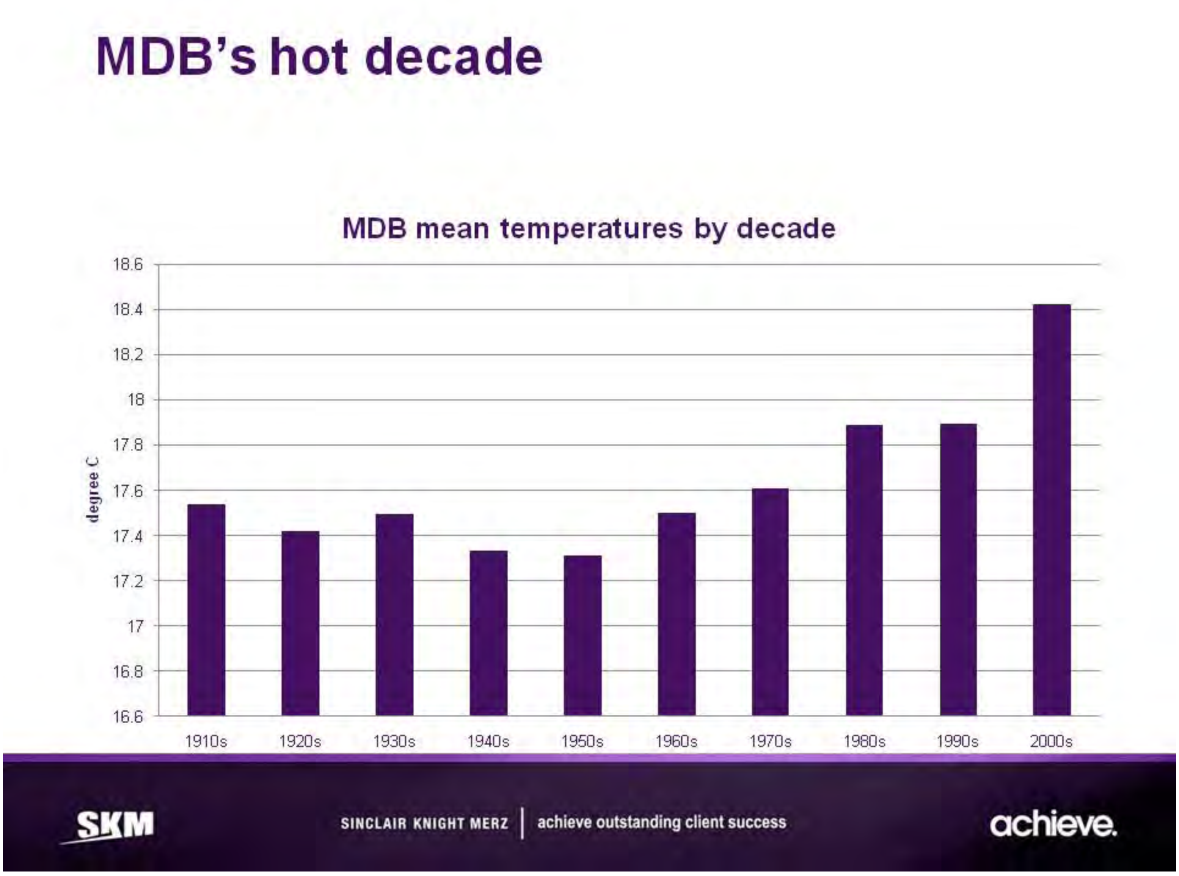
MDB's hot decade
MDB mean temperatures by decade
degree C
18.6
18.4
18.2
18
17.8
17.6
17.4
17.2
17
16.8
16.6
1910s
1920s
1930s
1940s
1950s
1960s
1970s
1980s
1990s
2000s
SKM
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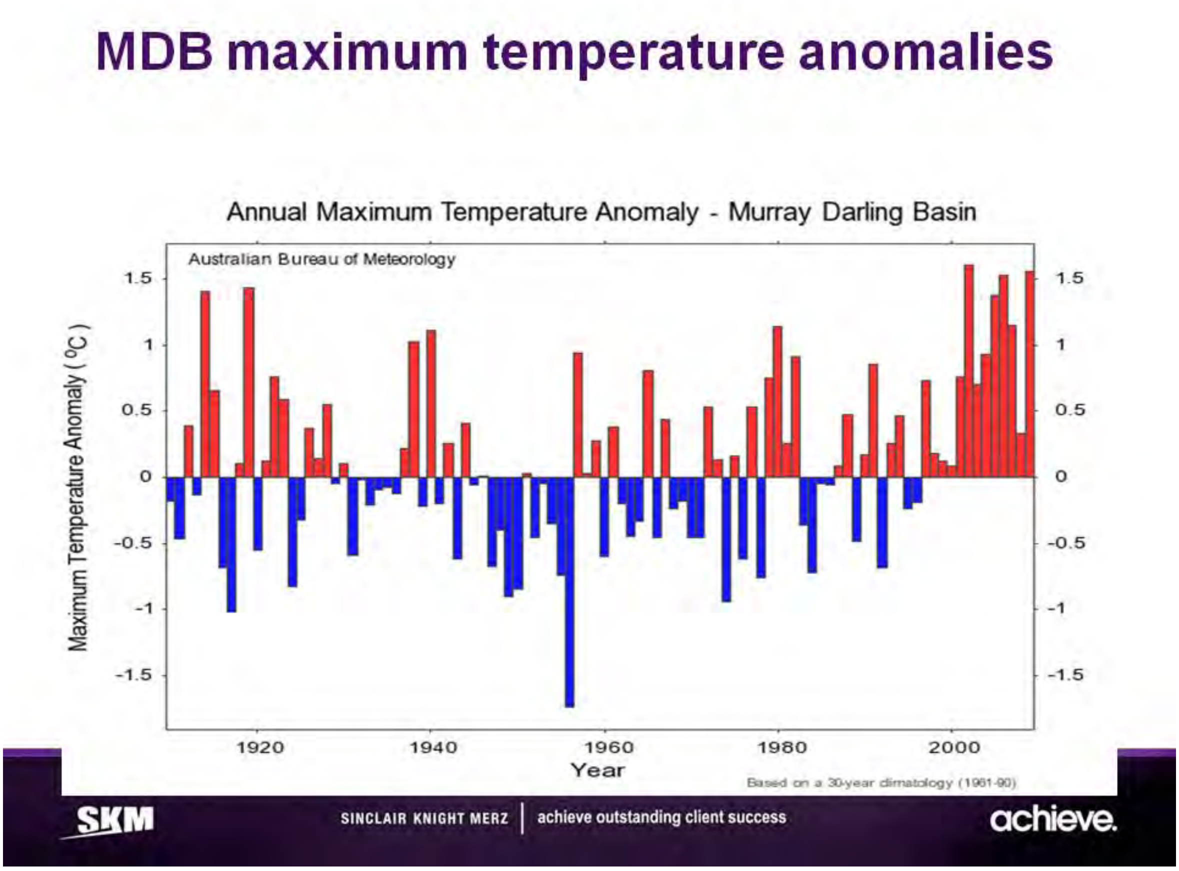
MDB maximum temperature anomalies
Annual Maximum Temperature Anomaly - Murray Darling Basin
Australian Bureau of Meteorology
Maximum Temperature Anomaly (°C)
1.5
1
0.5
0
-0.5
-1
-1.5
1920
1940
1960
1980
2000
Year
Based on a 30-year climatology (1961-90)
SKM
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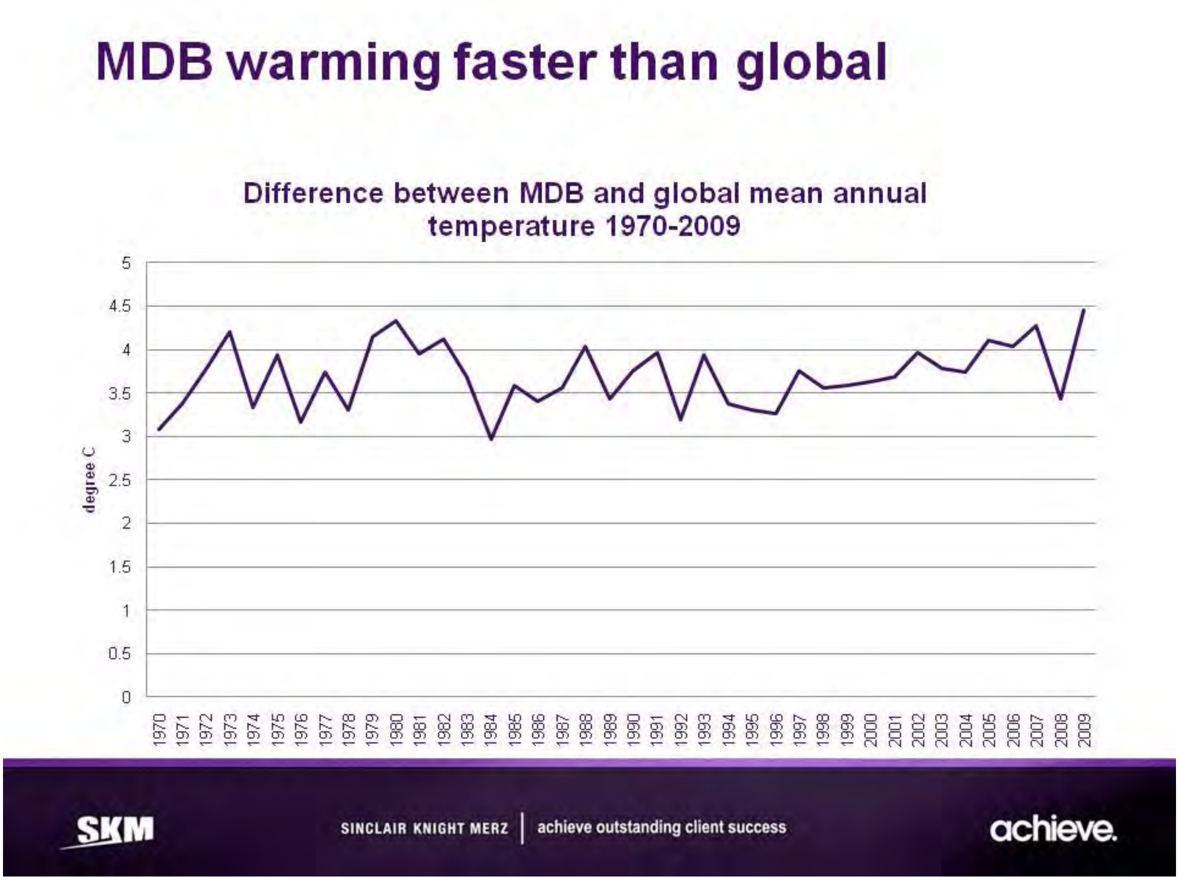
MDB warming faster than global
Difference between MDB and global mean annual temperature 1970-2009
degree C
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
SKM
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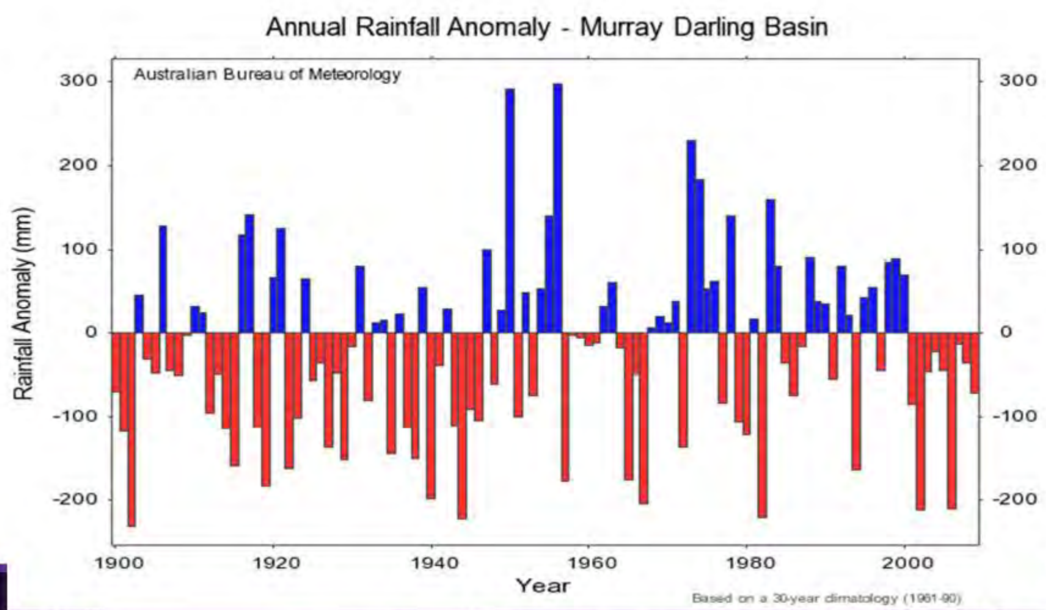
MDB rainfall



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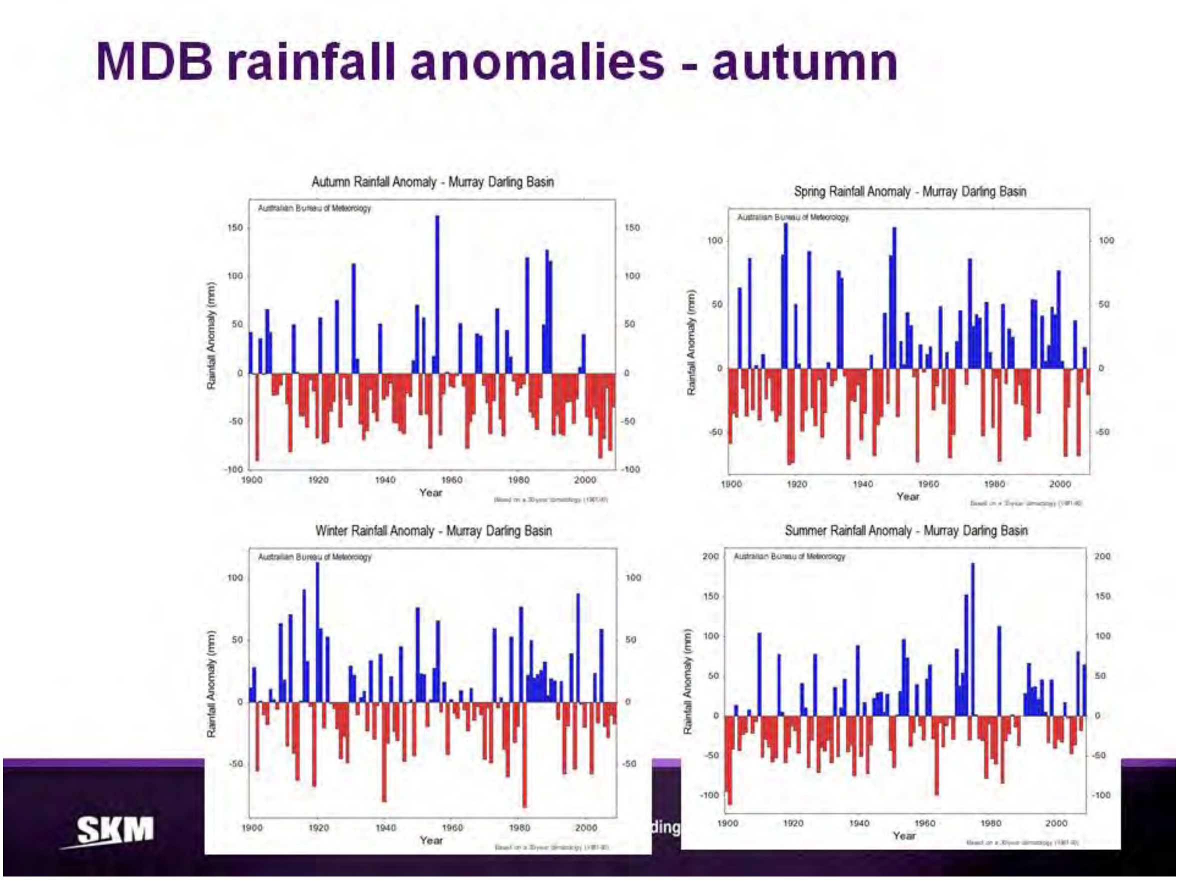
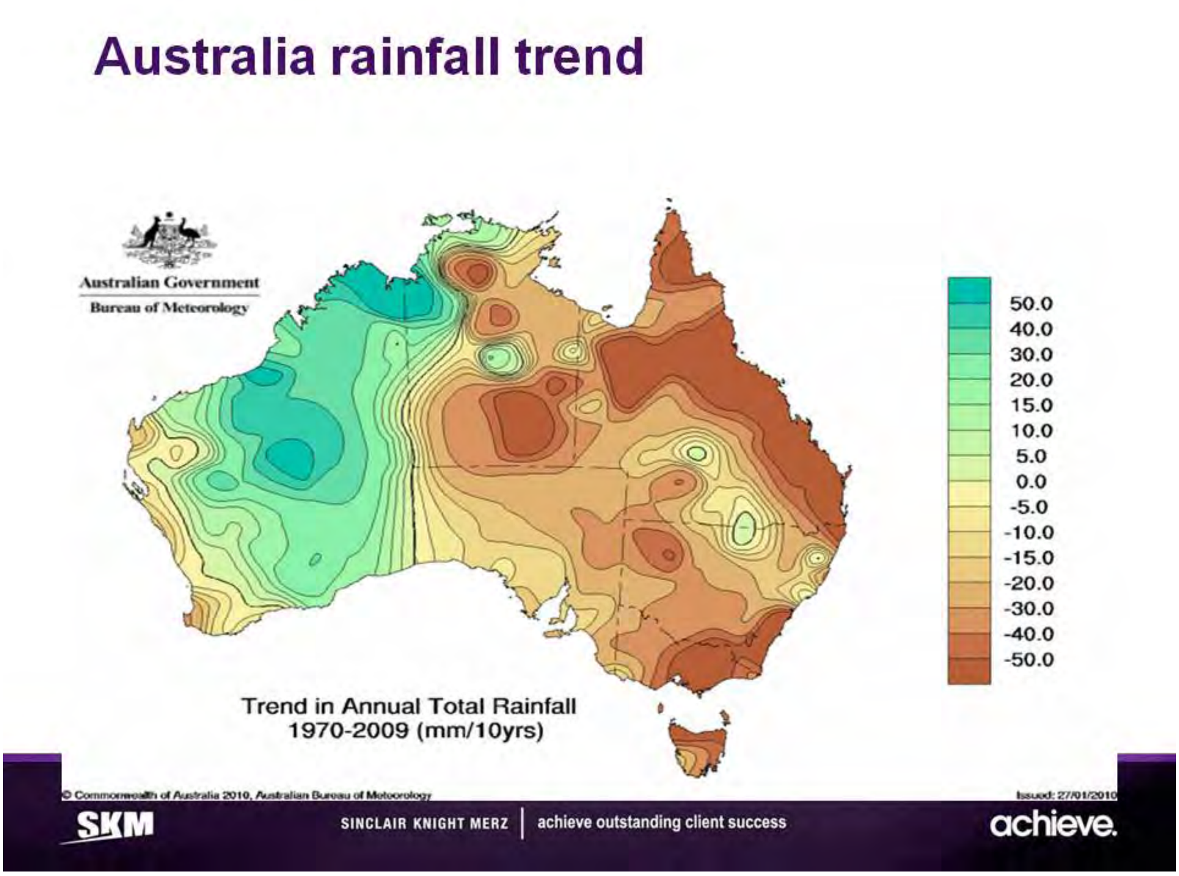

MDB rainfall anomalies - autumn
Autumn Rainfall Anomaly - Murray Darling Basin
Spring Rainfall Anomaly - Murray Darling Basin
Winter Rainfall Anomaly - Murray Darling Basin
Summer Rainfall Anomaly - Murray Darling Basin
Australian Bureau of Meteorology
Rainfall Anomaly (mm)
Year
SKM


Australia rainfall trend
Australian Government
Bureau of Meteorology
50.0
40.0
30.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-30.0
-40.0
-50.0
Trend in Annual Total Rainfall
1970-2009 (mm/10yrs)
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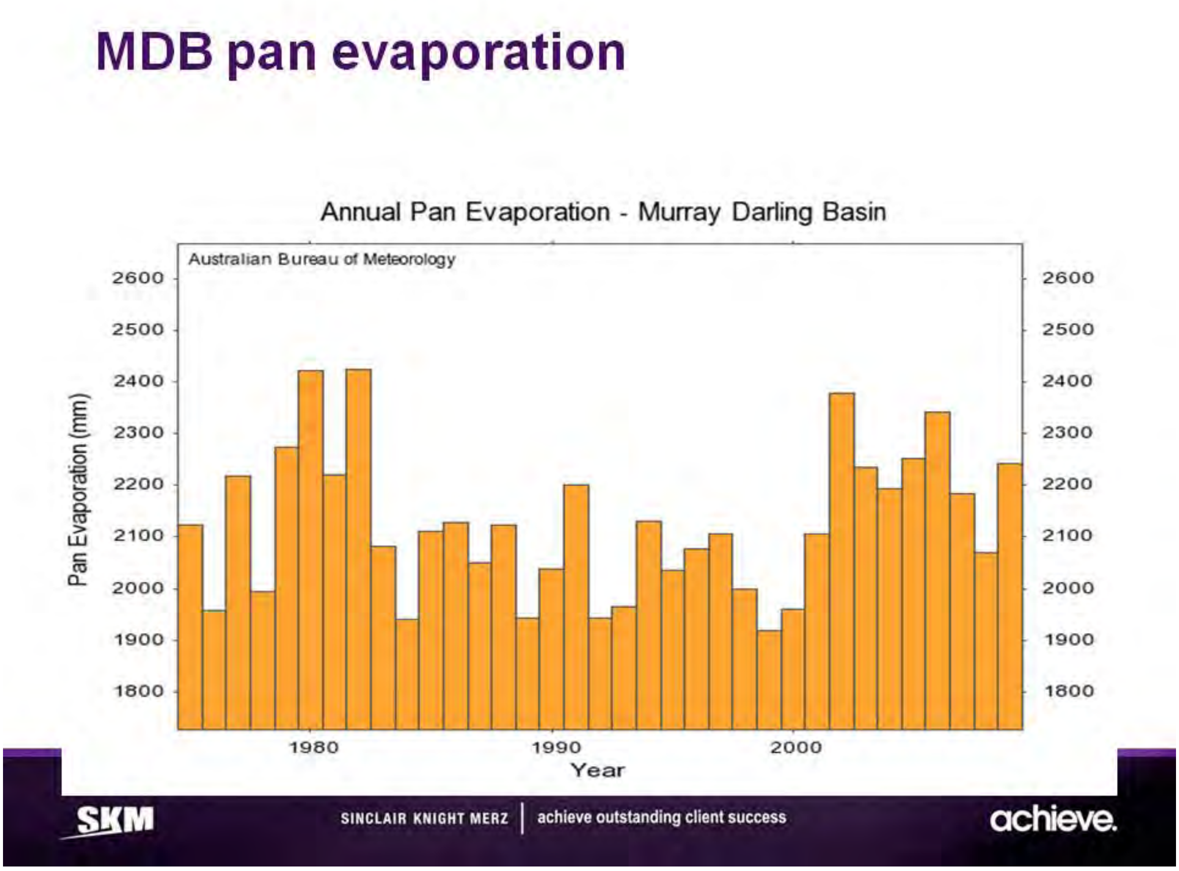
MDB pan evaporation
Annual Pan Evaporation - Murray Darling Basin
Australian Bureau of Meteorology
Pan Evaporation (mm)
2600
2500
2400
2300
2200
2100
2000
1900
1800
1980
1990
2000
Year
SKM
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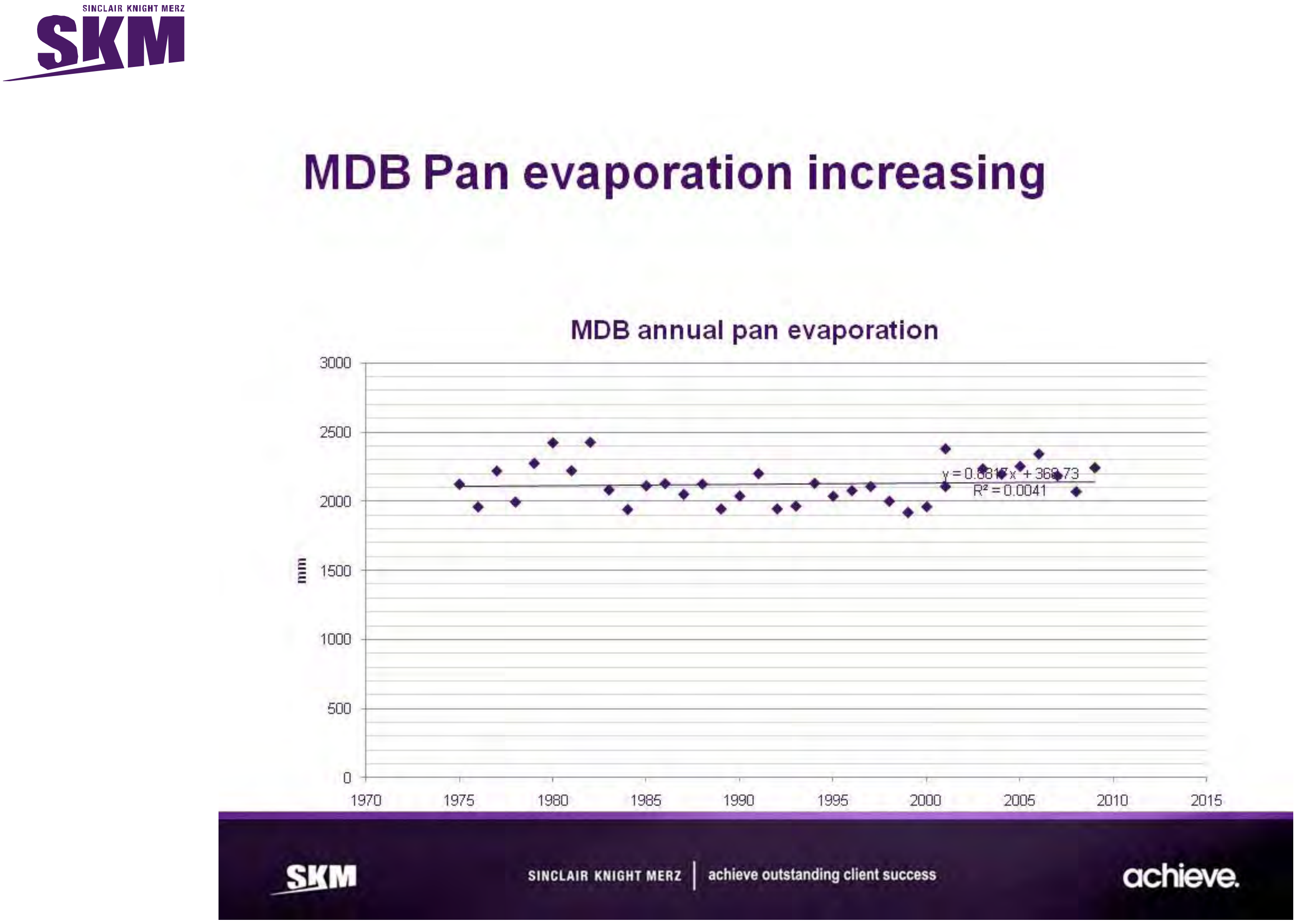
SINCLAIR KNIGHT MERZ
SKM
MDB Pan evaporation increasing
MDB annual pan evaporation
mm
3000
2500
2000
1500
1000
500
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
R² = 0.0041
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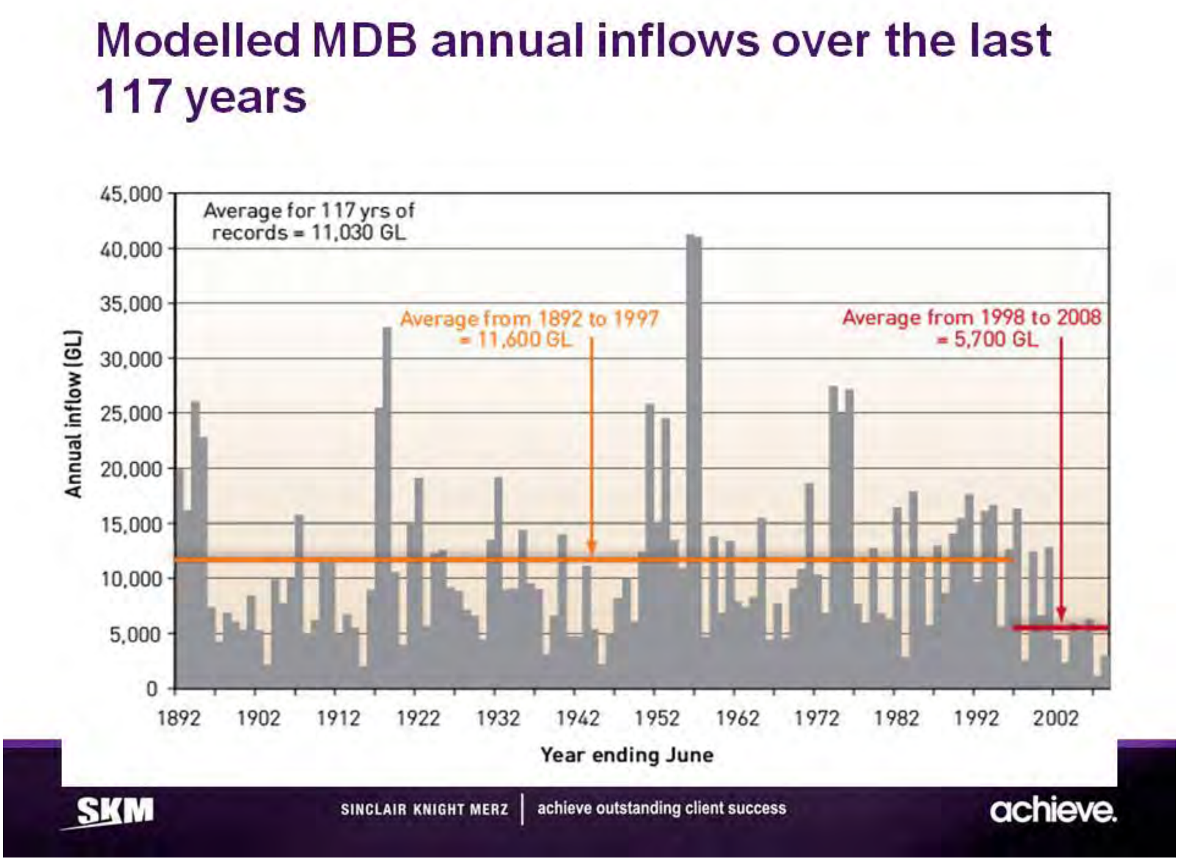
Modelled MDB annual inflows over the last 117 years
Average for 117 yrs of records = 11,030 GL
Average from 1892 to 1997 = 11,600 GL
Average from 1998 to 2008 = 5,700 GL
Annual inflow (GL)
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
1892
1902
1912
1922
1932
1942
1952
1962
1972
1982
1992
2002
Year ending June
SKM
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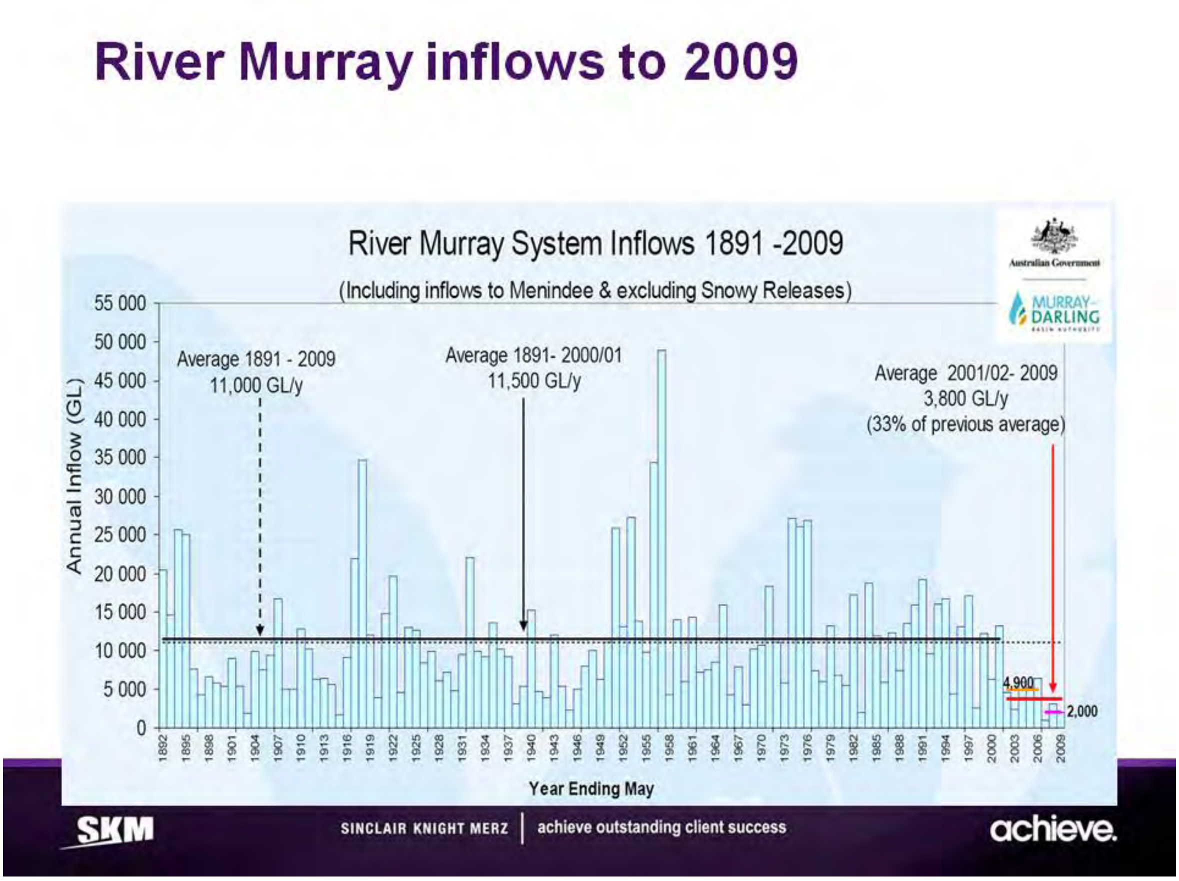
River Murray inflows to 2009
River Murray System Inflows 1891 -2009
(Including inflows to Menindee & excluding Snowy Releases)
Australian Government
MURRAY-DARLING BASIN AUTHORITY
Annual Inflow (GL)
55 000
50 000
45 000
40 000
35 000
30 000
25 000
20 000
15 000
10 000
5 000
0
Average 1891 - 2009
11,000 GL/y
Average 1891- 2000/01
11,500 GL/y
Average 2001/02- 2009
3,800 GL/y
(33% of previous average)
4,900
2,000
Year Ending May
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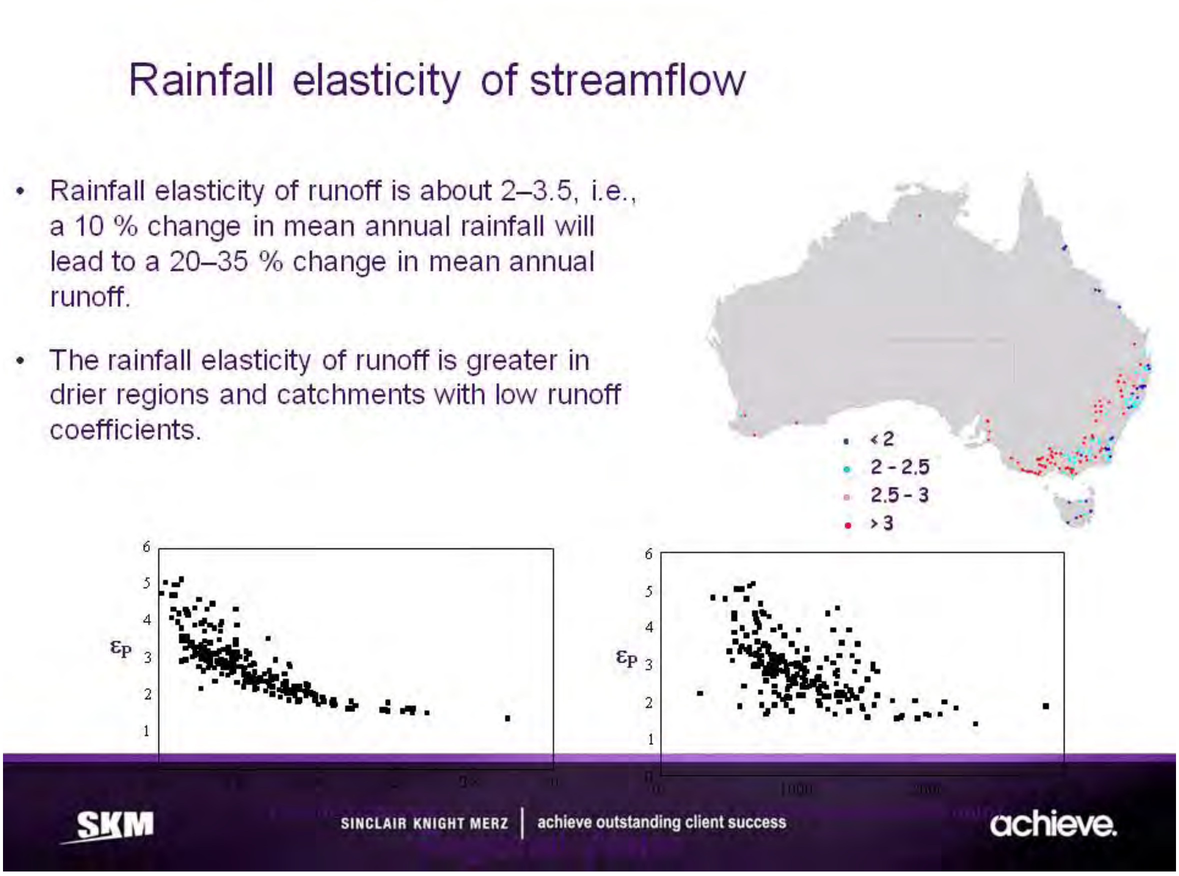
Rainfall elasticity of streamflow
• Rainfall elasticity of runoff is about 2–3.5, i.e., a 10 % change in mean annual rainfall will lead to a 20–35 % change in mean annual runoff.
• The rainfall elasticity of runoff is greater in drier regions and catchments with low runoff coefficients.
< 2
2 - 2.5
2.5 - 3
> 3
εP
εP
SKM
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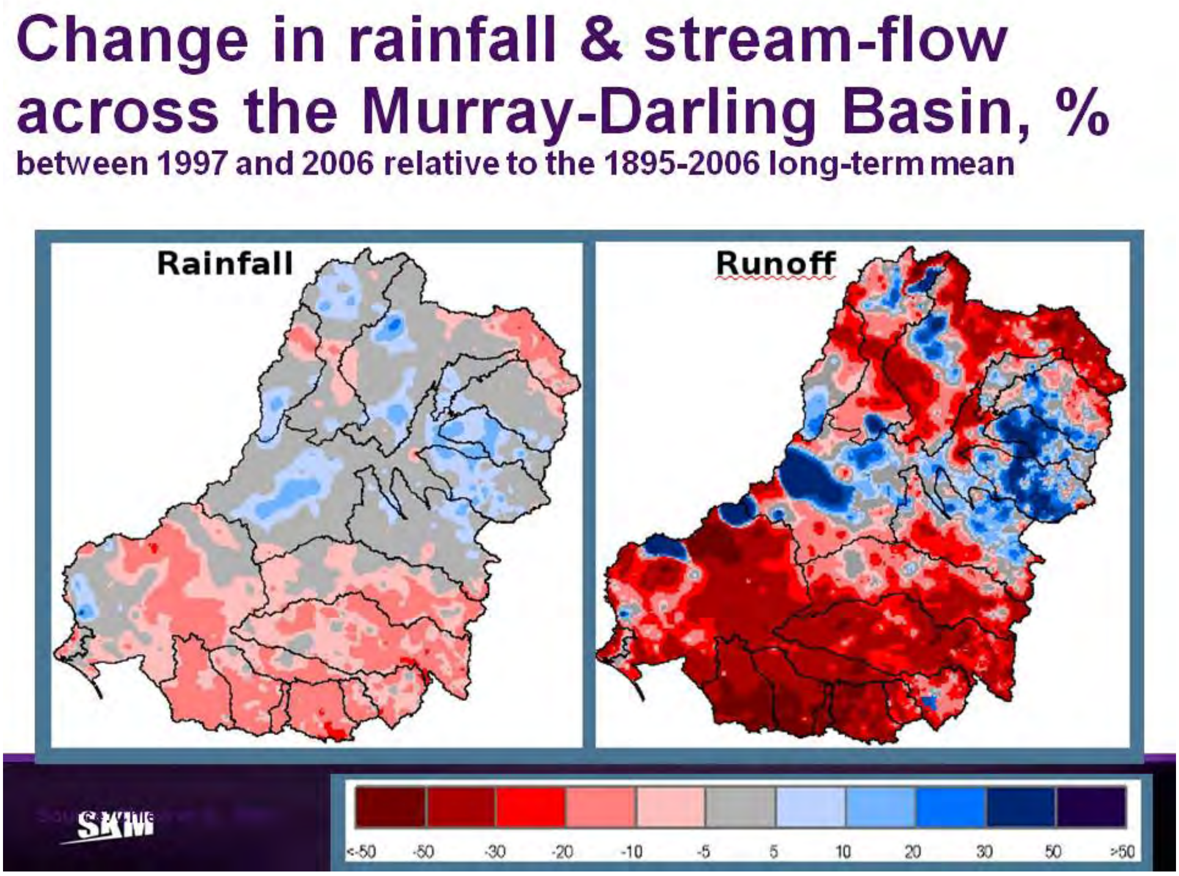
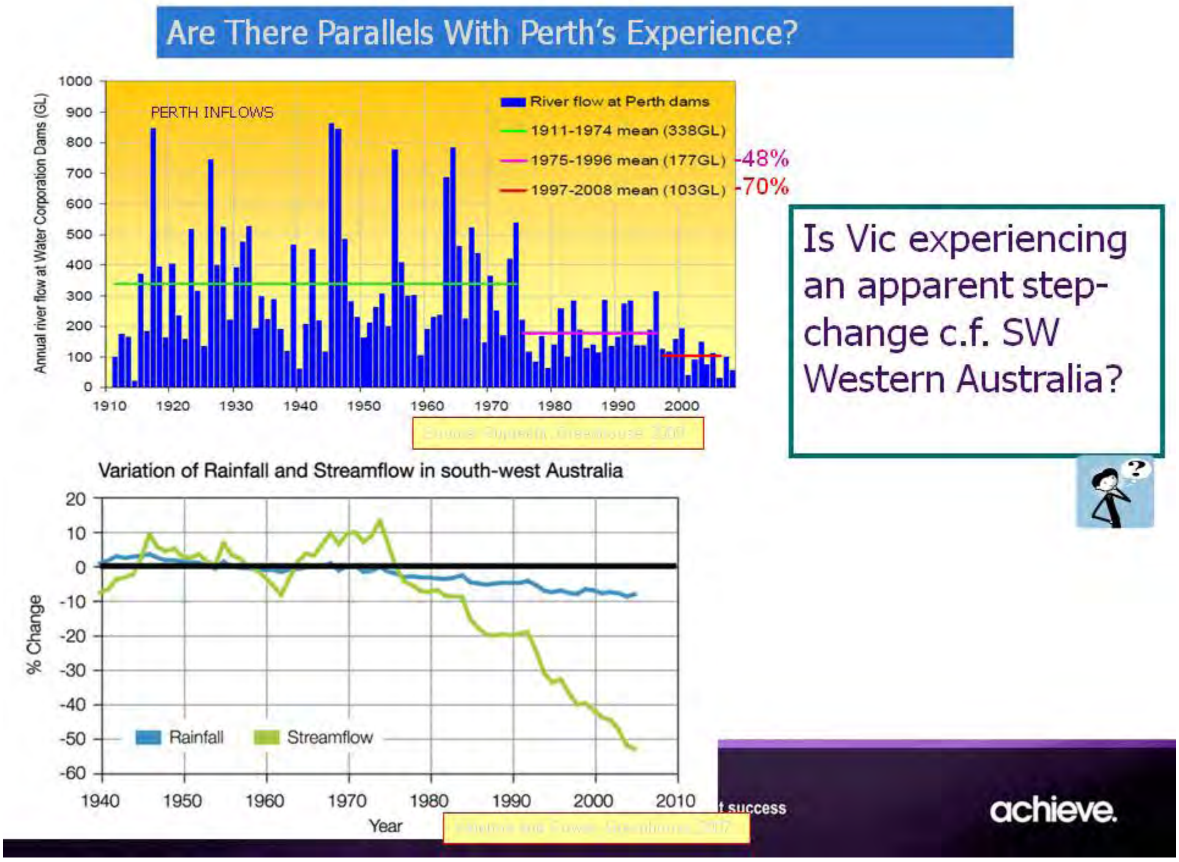

Change in rainfall & stream-flow across the Murray-Darling Basin, %
between 1997 and 2006 relative to the 1895-2006 long-term mean
Rainfall
Runoff
<-50 -50 -30 -20 -10 -5 5 10 20 30 50 >50


Are There Parallels With Perth's Experience?
PERTH INFLOWS
River flow at Perth dams
1911-1974 mean (338GL)
1975-1996 mean (177GL) -48%
1997-2008 mean (103GL) -70%
Annual river flow at Water Corporation Dams (GL)
Is Vic experiencing an apparent step-change c.f. SW Western Australia?
Variation of Rainfall and Streamflow in south-west Australia
% Change
Rainfall
Streamflow
Year
achieve.

Key points MDB temperatures, rainfall, evaporation, runoff

- Temperature anomalies a little higher than national/global average
- Rainfall anomaly has been negative for past 9 years
- Rainfall decline most pronounced in autumn
- Rainfall decline most pronounced in south-east corner
- Pan evaporation increasing in southern MDB
- Basin inflows (1998-2008) down 50% from (1895-1997)
- Murray inflows (2001-2009) down 67% from (1891-2000)
- Murray inflows (2007-2009) down 82% from (1891-2009)

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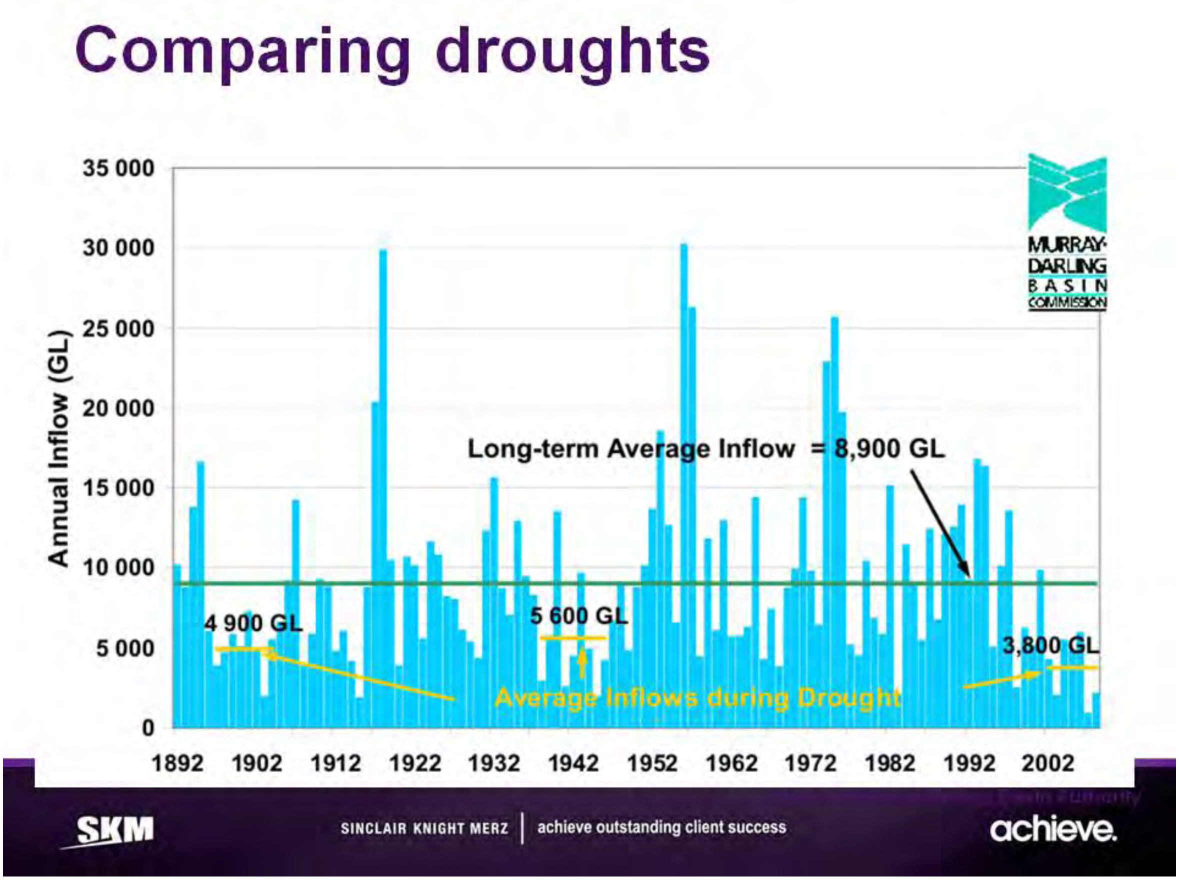

Comparing droughts
Annual Inflow (GL)
35 000
30 000
25 000
20 000
15 000
10 000
5 000
0
1892
1902
1912
1922
1932
1942
1952
1962
1972
1982
1992
2002
Long-term Average Inflow = 8,900 GL
4 900 GL
5 600 GL
3,800 GL
Average Inflows during Drought
MURRAY-DARLING BASIN COMMISSION
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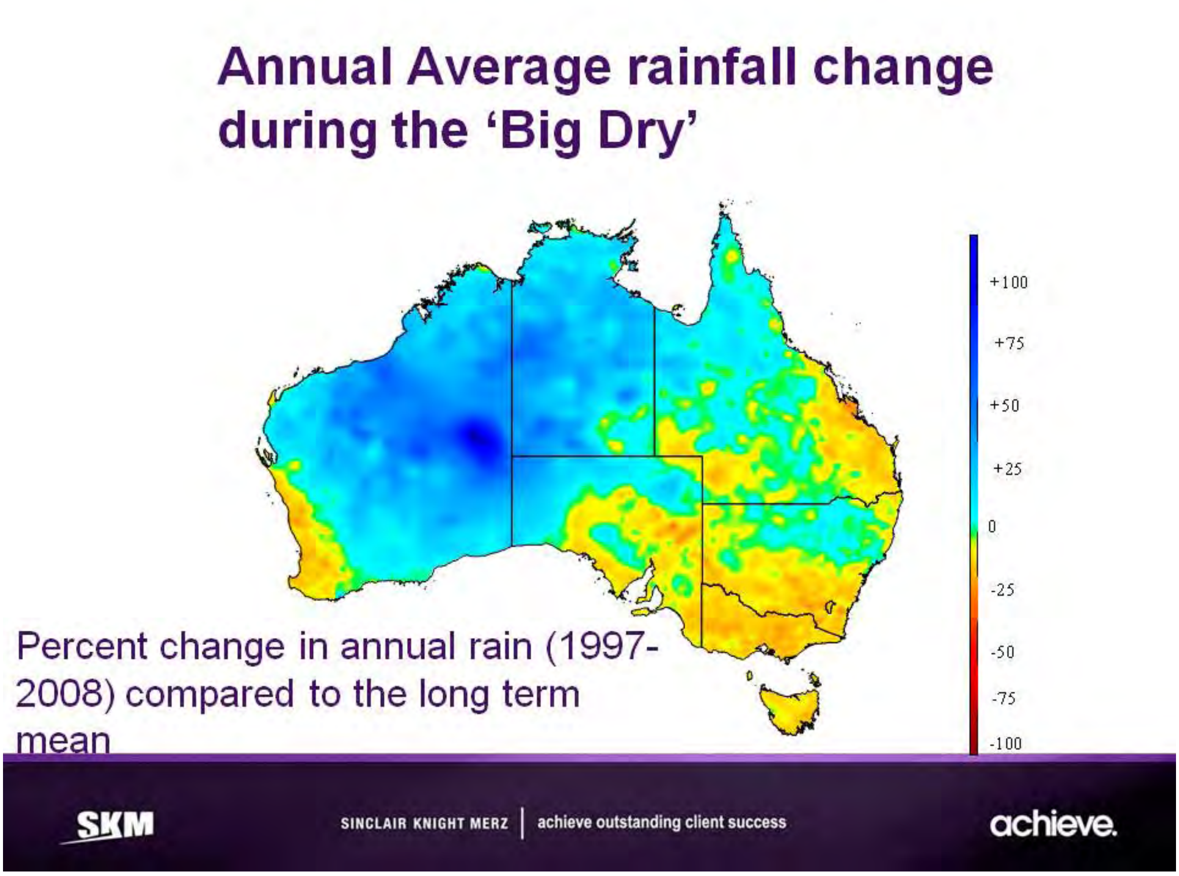
Annual Average rainfall change during the 'Big Dry'
+100
+75
+50
+25
0
-25
-50
-75
-100
Percent change in annual rain (1997-2008) compared to the long term mean
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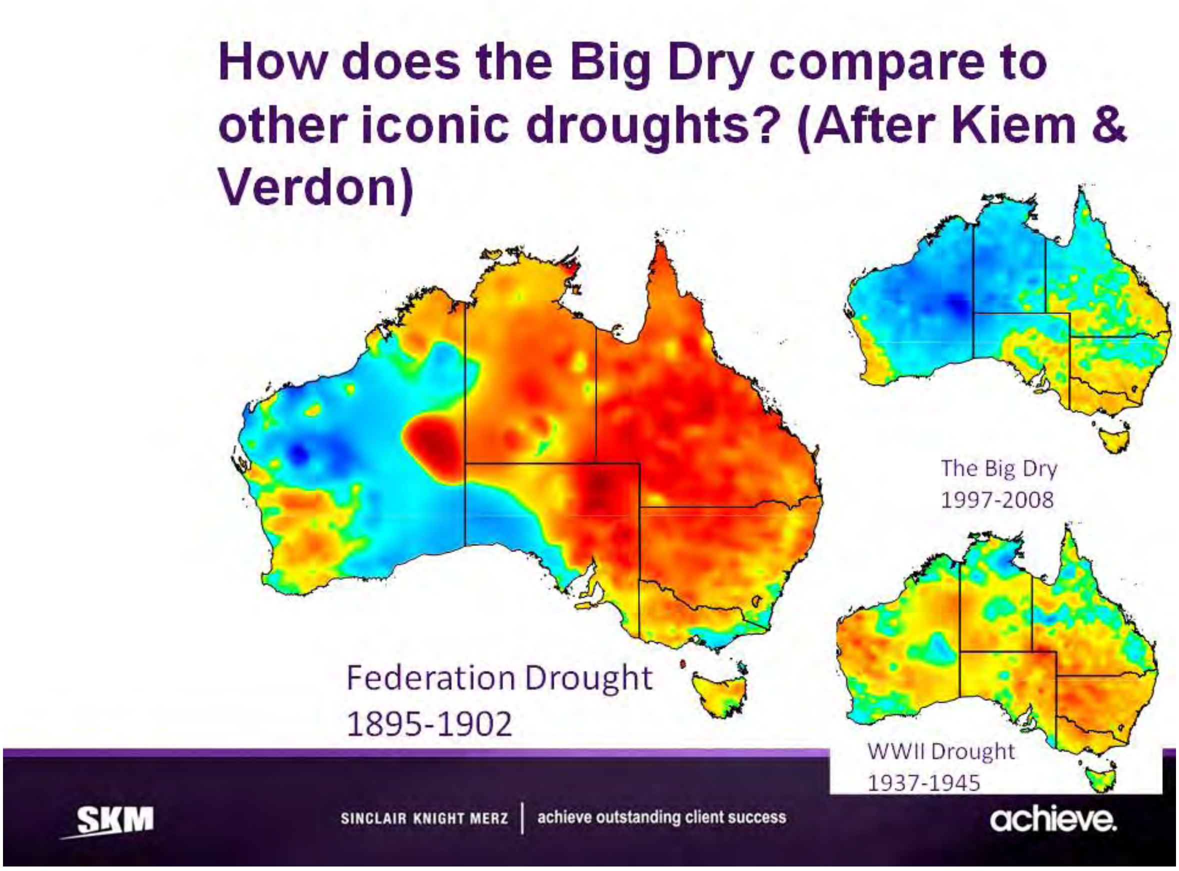
How does the Big Dry compare to other iconic droughts? (After Kiem & Verdon)
The Big Dry
1997-2008
Federation Drought
1895-1902
WWII Drought
1937-1945
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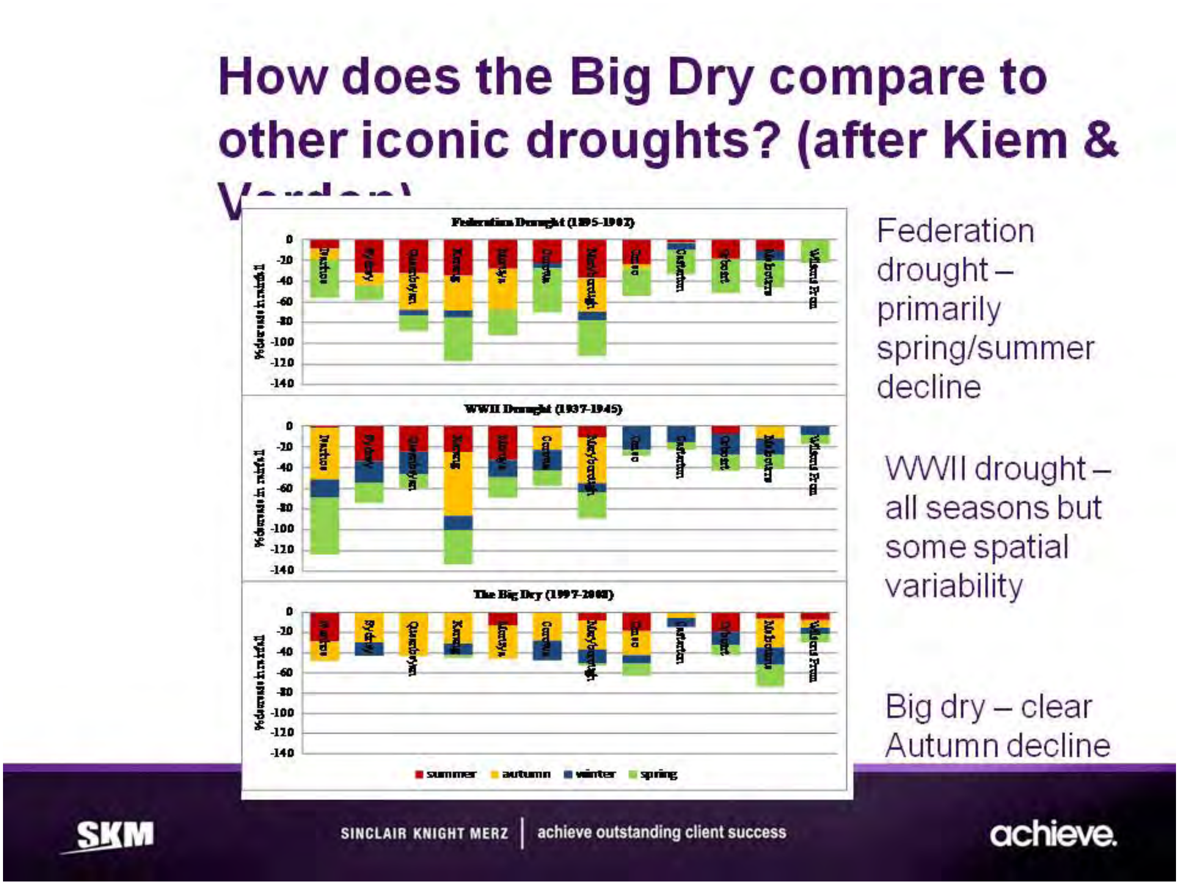
How does the Big Dry compare to other iconic droughts? (after Kiem &
Federation Drought (1895-1902)
WWII Drought (1937-1945)
The Big Dry (1997-2008)
summer
autumn
winter
spring
Federation drought – primarily spring/summer decline
WWII drought – all seasons but some spatial variability
Big dry – clear Autumn decline
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Daily rainfall statistics (after Kiem & Verdon)

Variable	Station	Federation summer	Federation autumn	Federation winter	Federation spring	WWII summer	WWII autumn	WWII winter	WWII spring	Big dry summer	Big dry autumn	Big dry winter	Big dry spring
% difference in number of wet days per yr	Ivanhoe	-14	-26	3	-30	-38	-36	-22	-40	4	-13	6	0
	Sydney	-10	-13	25	-11	-27	-2	6	0	-4	-7	-3	-1
	Queanbeyan	-35	-30	-22	-19	-20	-8	-12	-7	28	-23	29	2
	Kerang	-34	-32	-17	-43	-17	-33	-20	-27	16	-16	-8	-4
	Moruya	-16	-15	24	-19	-5	0	3	-1	-1	-14	-2	-8
	Corowa	-31	-17	-16	-38	-26	-16	-16	-16	-4	-20	-13	-8
	Maryborough	47	58	-8	-29	-13	-6	-14	-17	-4	-21	-15	-4
	Omeo	-16	8	5	-22	-5	5	-11	-7	-2	-15	-5	-3
	Casterton	-9	10	-11	-12	21	-4	-3	-11	-6	-8	-5	3
	Orbost	-24	-13	24	-32	0	12	-4	-5	11	-1	-5	5
	Melbourne	0	2	-4	-21	-4	0	-1	-11	-12	-20	-21	-17
	Wilsons Promontory	-10	-6	-6	-14	12	8	6	3	-5	-13	-11	-5
% difference in average daily rainfall intensity	Ivanhoe	-19	-14	-5	-22	-4	4	-11	-8	-34	-41	-18	-12
	Sydney	-26	-18	5	-7	-21	-3	-21	-14	-3	1	15	-1
	Queanbeyan	11	12	38	13	-15	-20	-30	-19	-13	-29	-5	-15
	Kerang	24	37	41	20	-21	-27	-7	-10	-22	-34	-21	-9
	Moruya	9	-3	41	-19	0	32	-18	5	-13	-30	18	-6
	Corowa	18	19	23	-1	-9	15	-3	-11	-5	-15	-11	-10
	Maryborough	-2	-5	17	0	-19	-22	-4	-13	-12	-36	-29	-18
	Omeo	8	5	4	-7	7	13	3	12	-23	-36	-18	-17
	Casterton	11	-5	14	-14	12	-8	-7	-10	-8	-16	-16	1
	Orbost	55	50	58	51	-17	5	-24	2	-29	-31	-15	-26
	Melbourne	2	21	0	-18	-4	-11	-9	-5	-9	-10	-2	-10
	Wilsons Prom	24	19	4	-12	-7	3	-8	-10	-19	-16	-5	-13

Federation drought – primarily reduction in no. wet days

WWII drought – reduction in no. wet days & rainfall intensity

Big Dry–reduction in rainfall intensity

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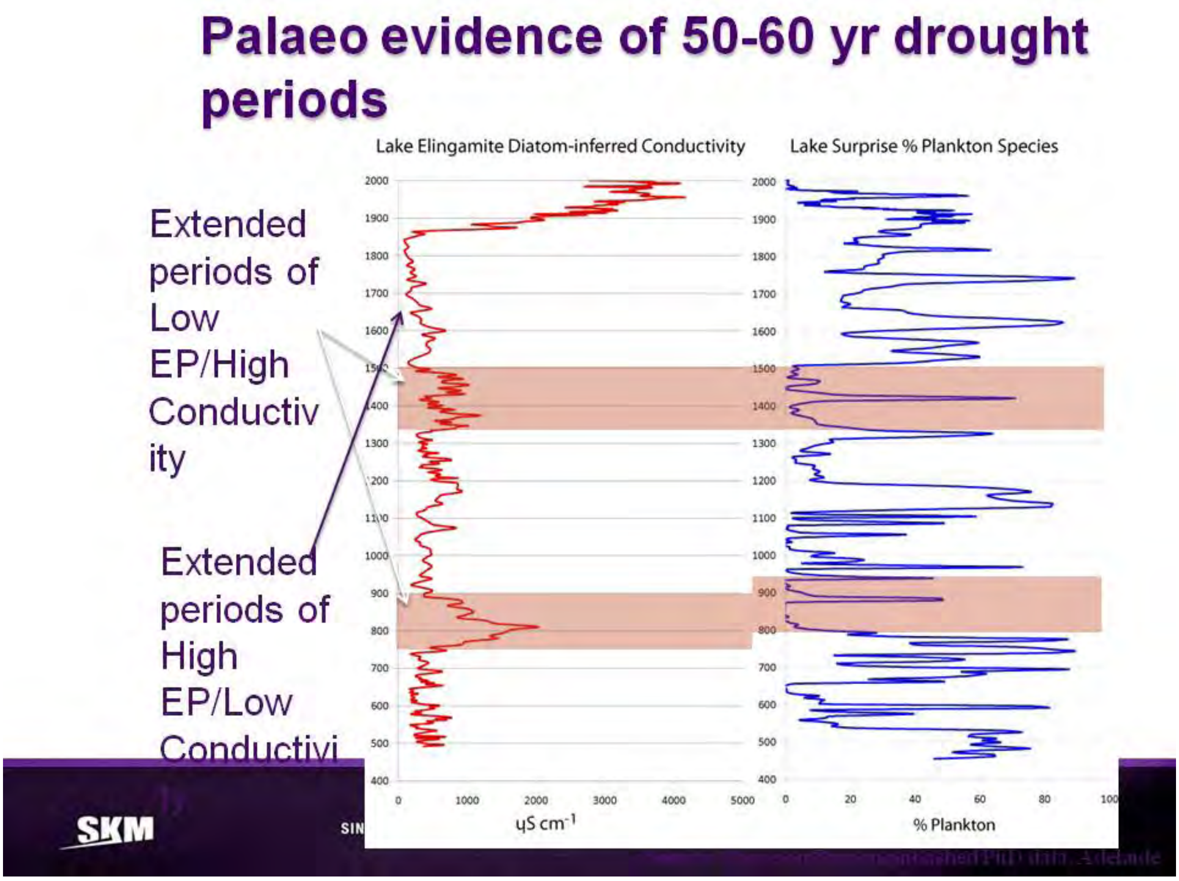
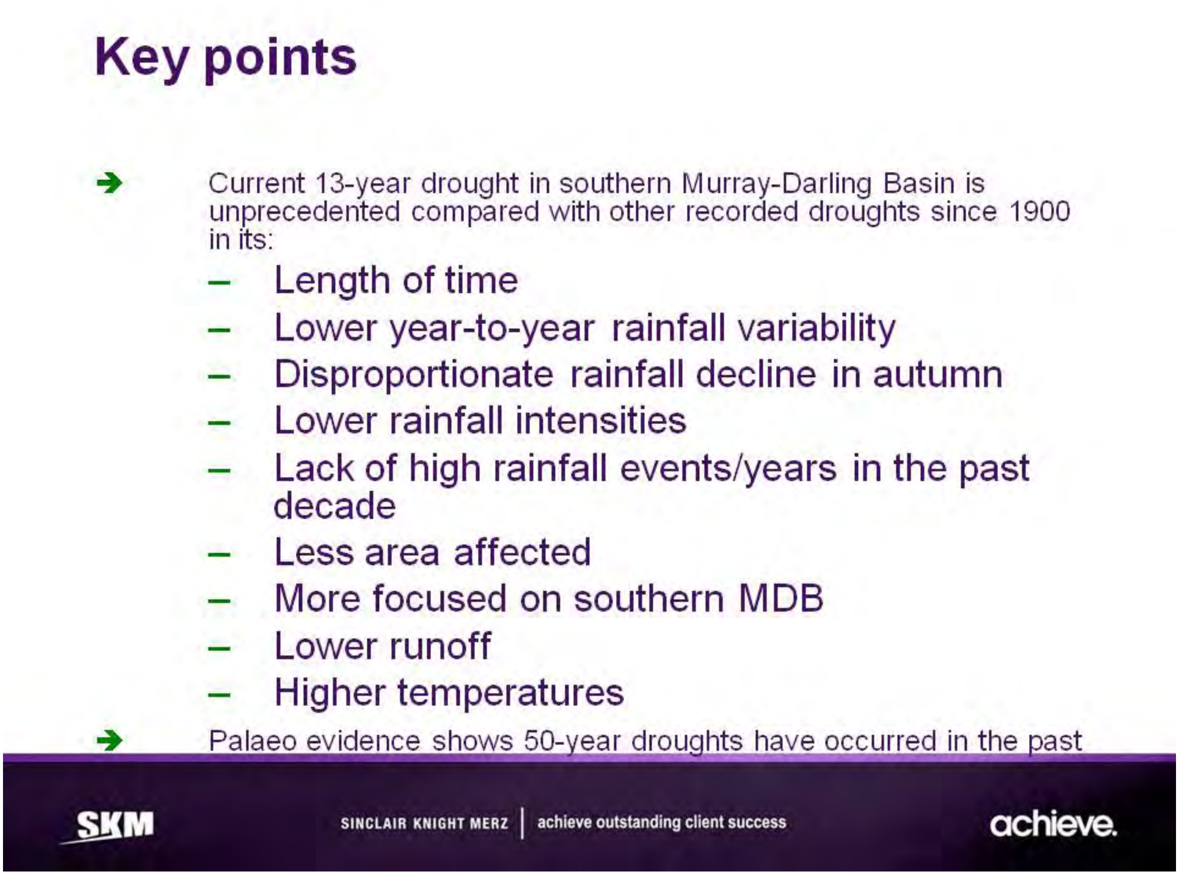


Palaeo evidence of 50-60 yr drought periods
Extended periods of Low EP/High Conductivity
Extended periods of High EP/Low Conductivi
Lake Elingamite Diatom-inferred Conductivity
Lake Surprise % Plankton Species
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
0
1000
2000
3000
4000
5000
µS cm-1
0
20
40
60
80
100
% Plankton
SKM


Key points
Current 13-year drought in southern Murray-Darling Basin is unprecedented compared with other recorded droughts since 1900 in its:
– Length of time
– Lower year-to-year rainfall variability
– Disproportionate rainfall decline in autumn
– Lower rainfall intensities
– Lack of high rainfall events/years in the past decade
– Less area affected
– More focused on southern MDB
– Lower runoff
– Higher temperatures
Palaeo evidence shows 50-year droughts have occurred in the past
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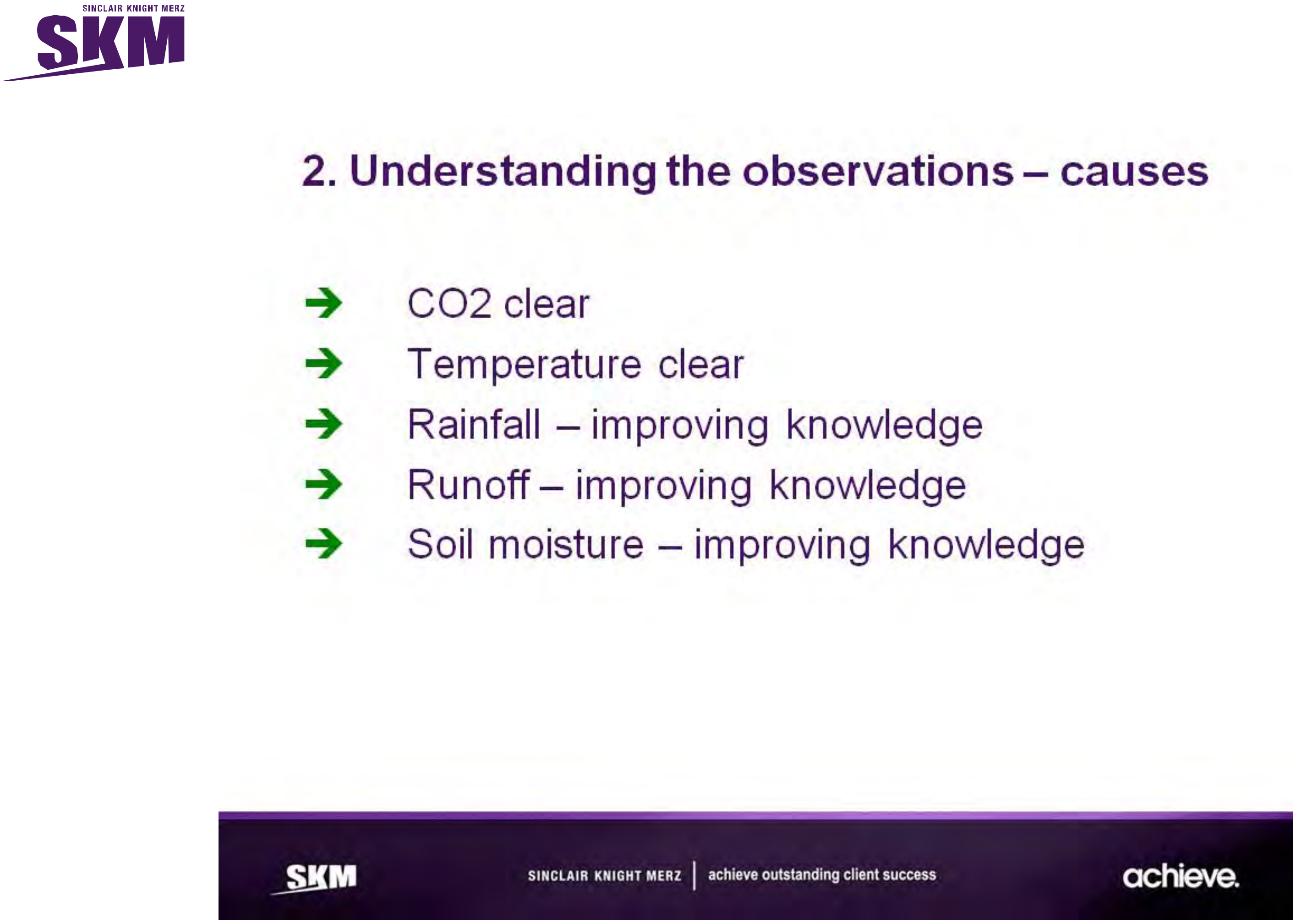
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2. Understanding the observations – causes
CO2 clear
Temperature clear
Rainfall – improving knowledge
Runoff – improving knowledge
Soil moisture – improving knowledge
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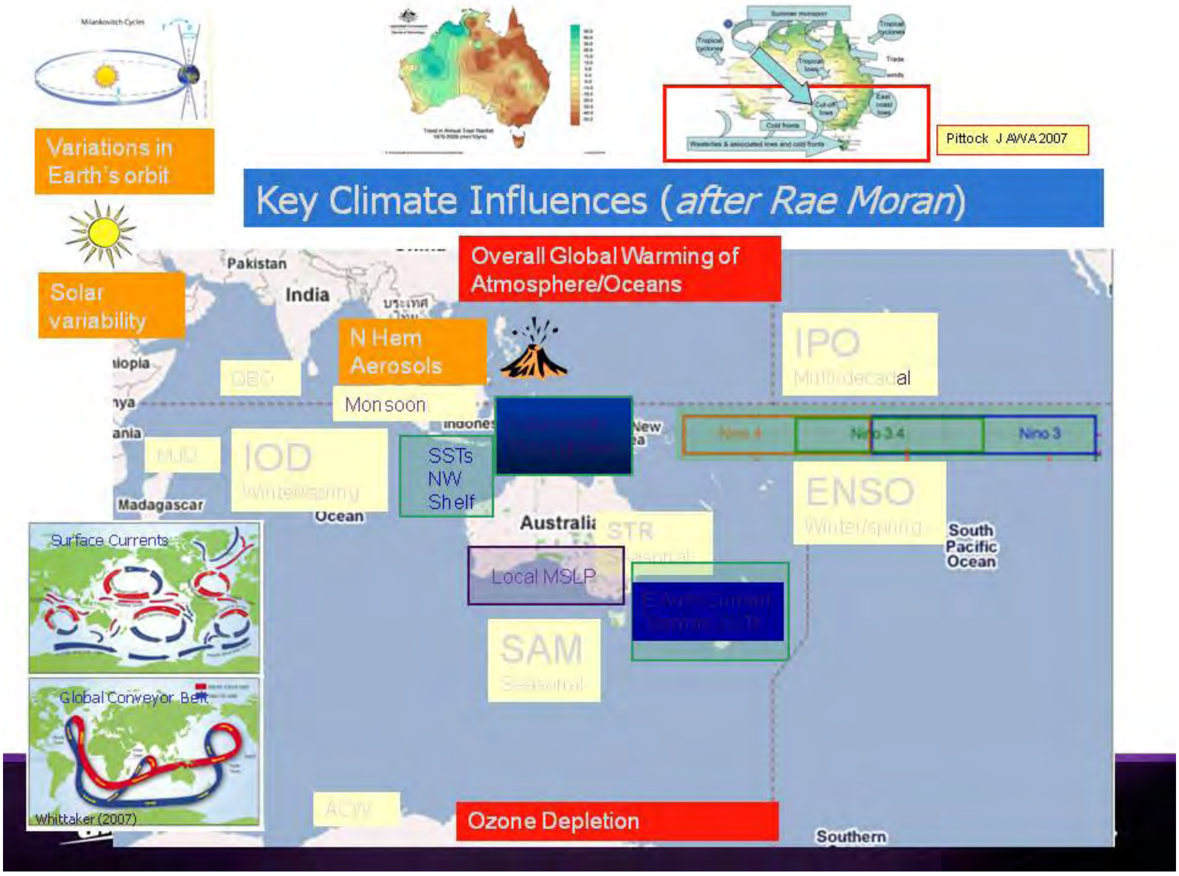
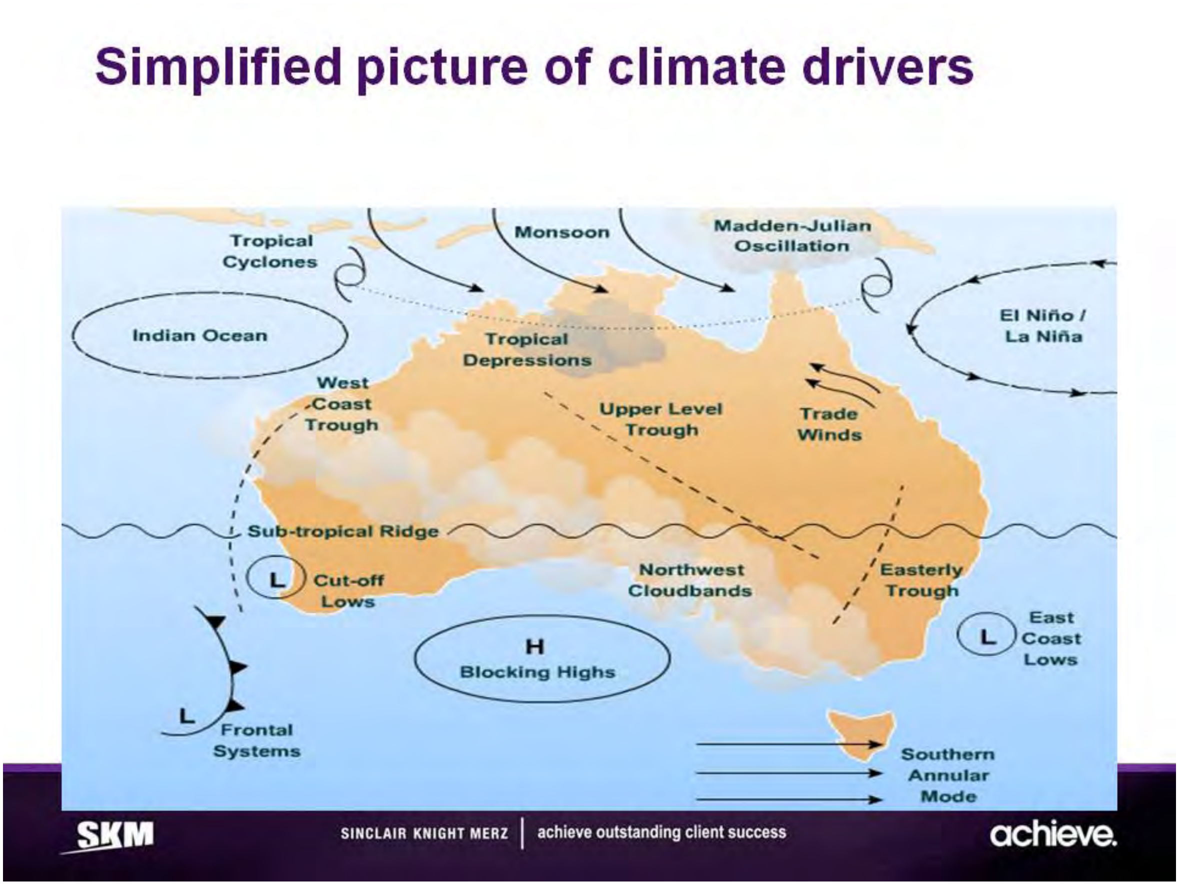

Key Climate Influences (after Rae Moran)
Variations in Earth's orbit
Solar variability
Pittock J AWA 2007
Overall Global Warming of Atmosphere/Oceans
N Hem Aerosols
Monsoon
IPO
IOD
SSTs NW Shelf
Nino 3.4
Nino 3
ENSO
STR
Local MSLP
SAM
Surface Currents
Global Conveyor Belt
Whittaker (2007)
Ozone Depletion
Pakistan
India
Madagascar
Australia
South Pacific Ocean
Southern


Simplified picture of climate drivers
Tropical Cyclones
Monsoon
Madden-Julian Oscillation
Indian Ocean
Tropical Depressions
El Niño / La Niña
West Coast Trough
Upper Level Trough
Trade Winds
Sub-tropical Ridge
Cut-off Lows
Northwest Cloudbands
Easterly Trough
East Coast Lows
H
Blocking Highs
L
Frontal Systems
Southern Annular Mode
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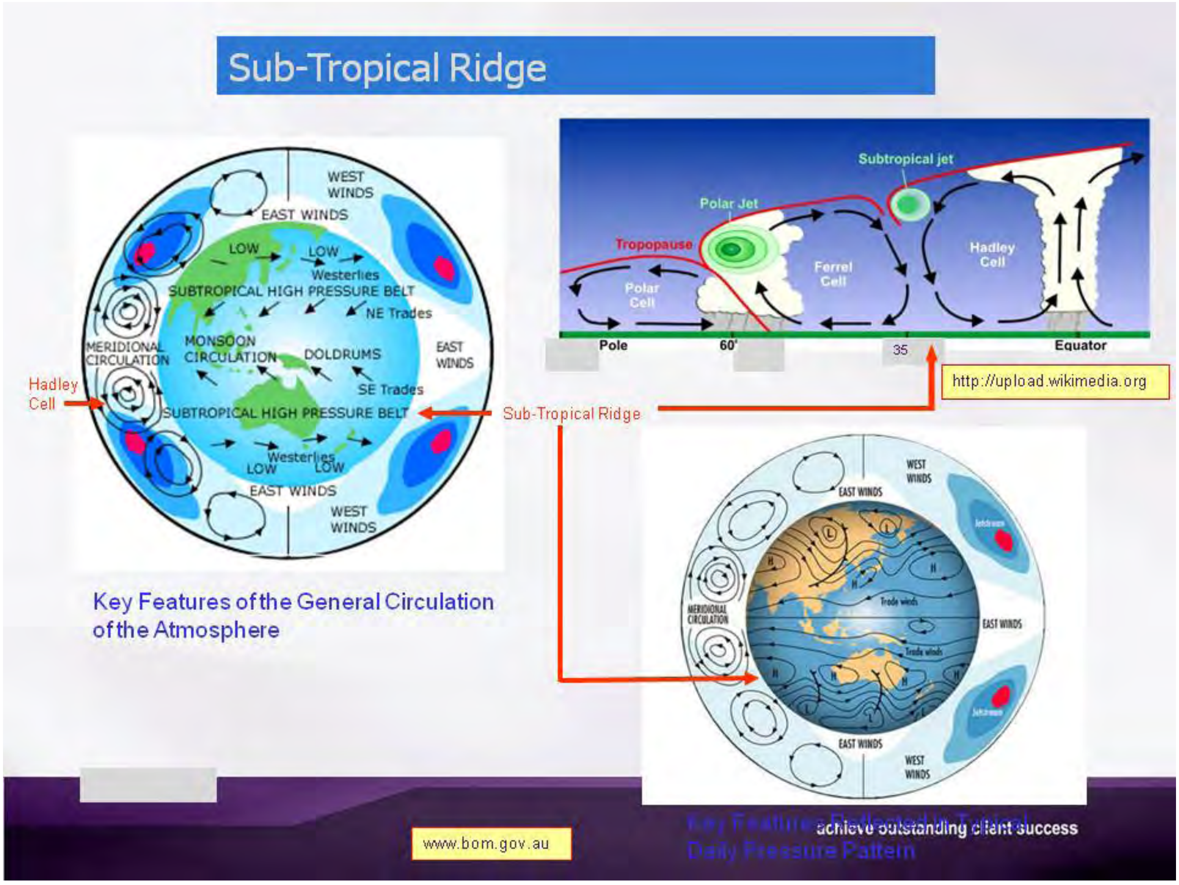
Sub-Tropical Ridge
WEST WINDS
EAST WINDS
LOW
LOW
Westerlies
SUBTROPICAL HIGH PRESSURE BELT
NE Trades
MERIDIONAL CIRCULATION
MONSOON CIRCULATION
DOLDRUMS
EAST WINDS
SE Trades
Hadley Cell
SUBTROPICAL HIGH PRESSURE BELT
Sub-Tropical Ridge
Westerlies
LOW
LOW
EAST WINDS
WEST WINDS
Key Features of the General Circulation of the Atmosphere
Subtropical jet
Polar Jet
Tropopause
Hadley Cell
Ferrel Cell
Polar Cell
Pole
60'
35
Equator
http://upload.wikimedia.org
www.bom.gov.au
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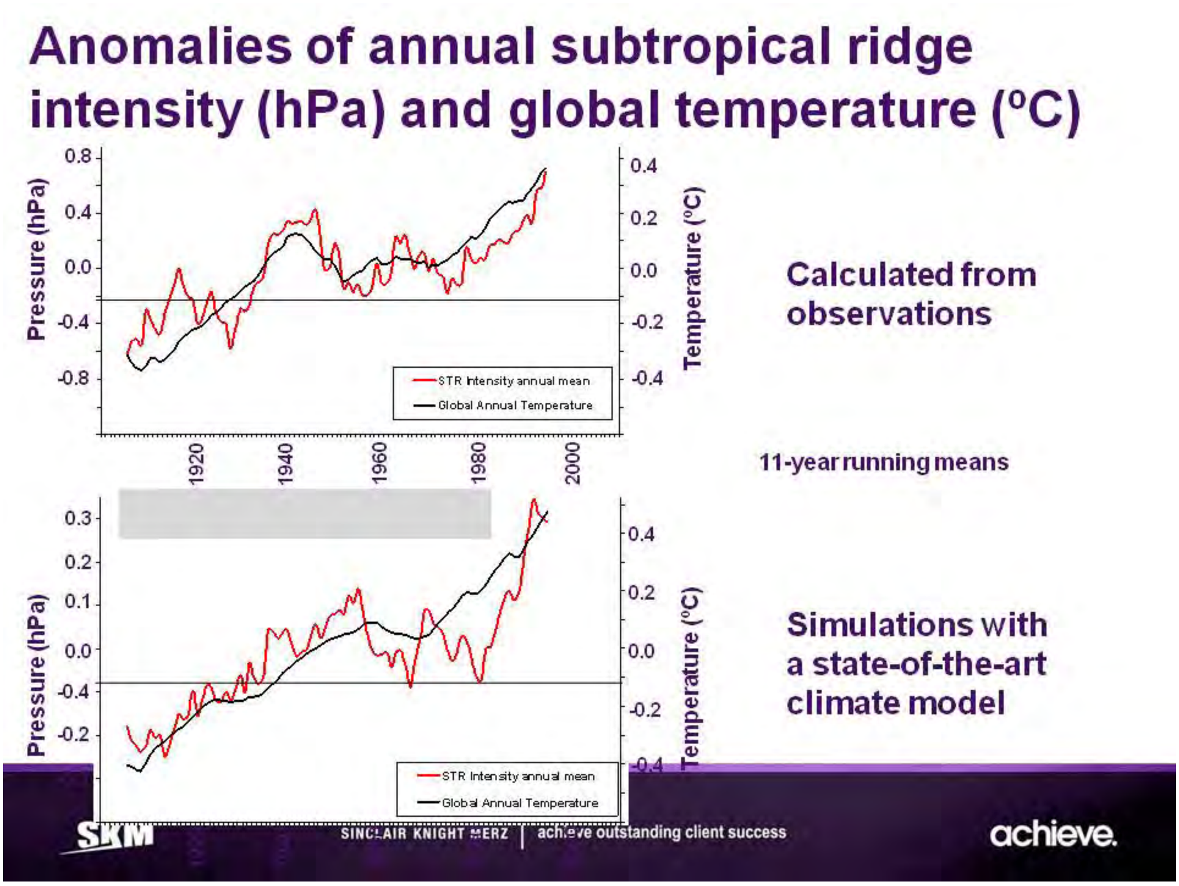
Anomalies of annual subtropical ridge intensity (hPa) and global temperature (°C)
Pressure (hPa)
Temperature (°C)
STR Intensity annual mean
Global Annual Temperature
Calculated from observations
11-year running means
Simulations with a state-of-the-art climate model
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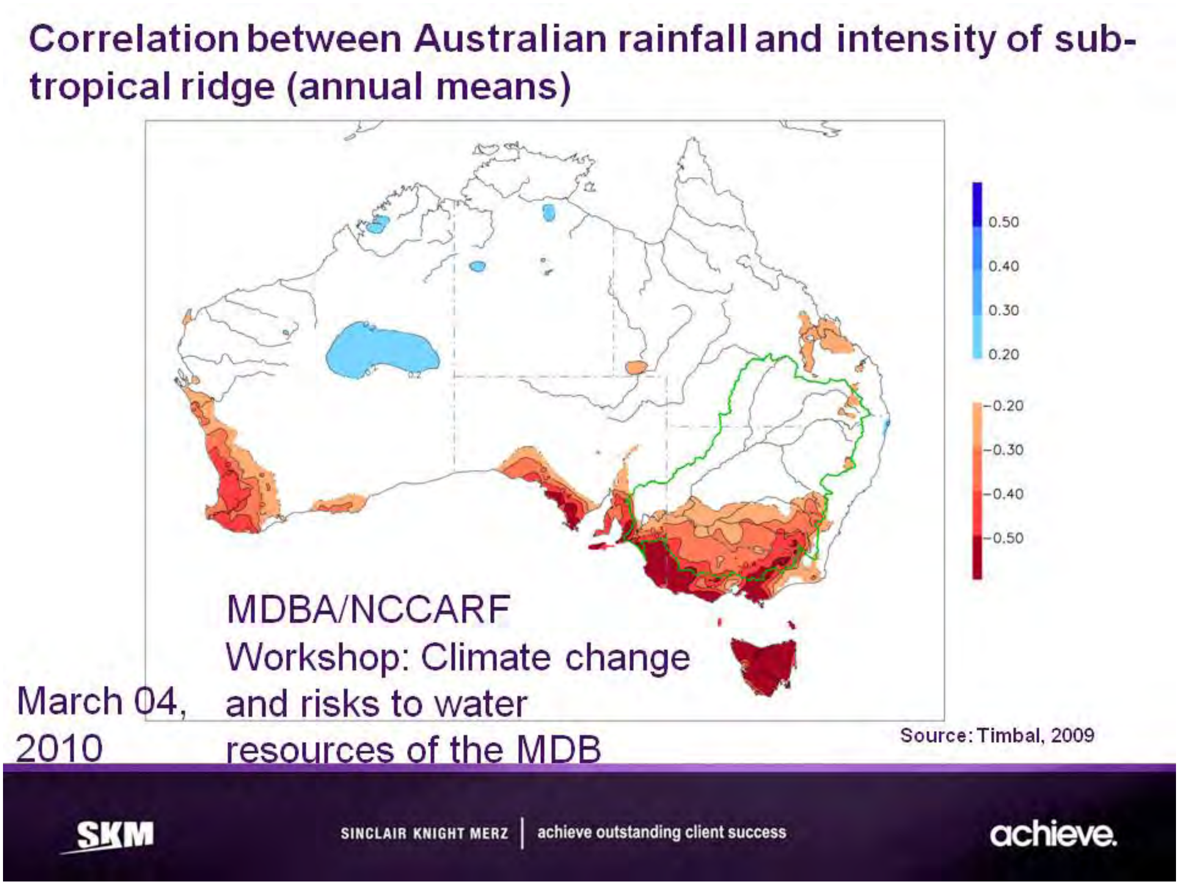
Correlation between Australian rainfall and intensity of sub-tropical ridge (annual means)
0.50
0.40
0.30
0.20
-0.20
-0.30
-0.40
-0.50
MDBA/NCCARF Workshop: Climate change and risks to water resources of the MDB
March 04, 2010
Source: Timbal, 2009
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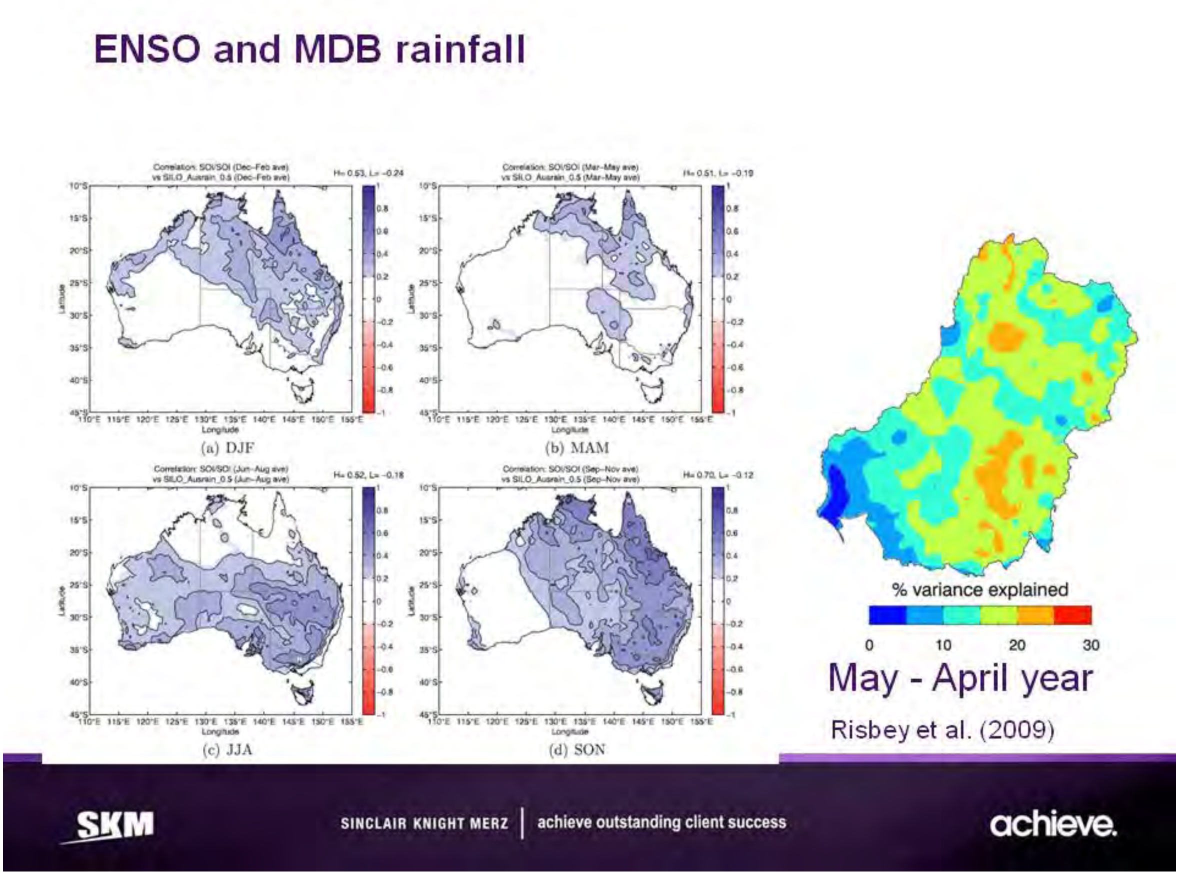
ENSO and MDB rainfall
(a) DJF
(b) MAM
(c) JJA
(d) SON
% variance explained
0
10
20
30
May - April year
Risbey et al. (2009)
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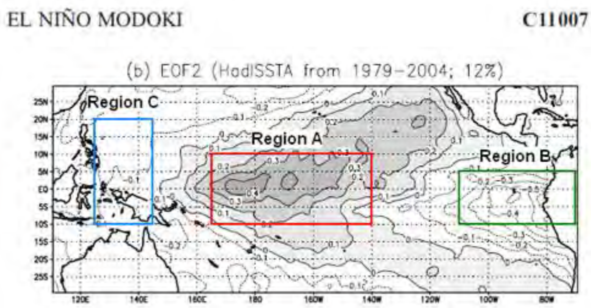
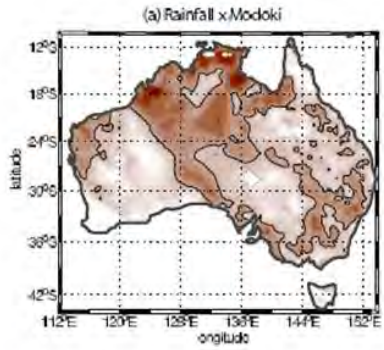
ENSO flavours – ENSO Modoki





Cai & Cowan (2009)

Taschetto & England (2009)

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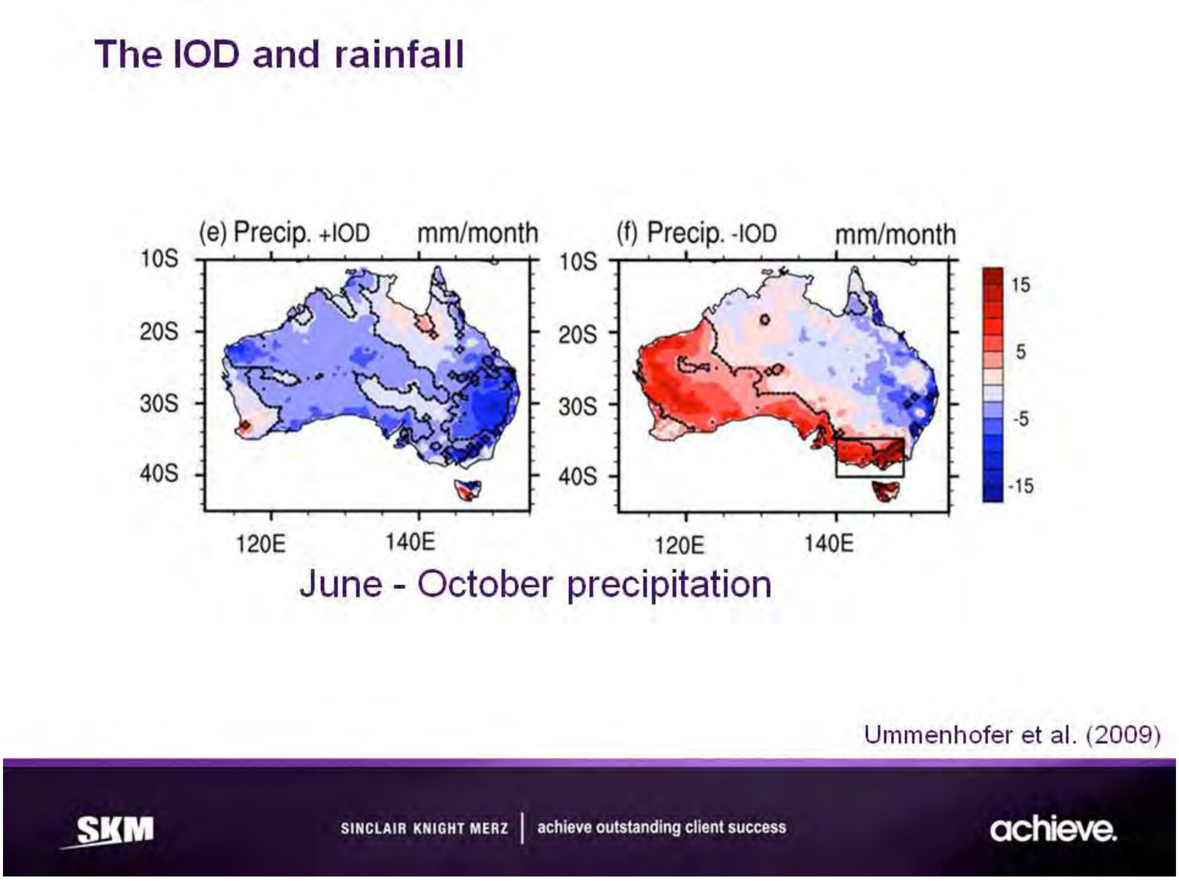
The IOD and rainfall
(e) Precip. +IOD
mm/month
(f) Precip. -IOD
mm/month
10S
20S
30S
40S
120E
140E
15
5
-5
-15
June - October precipitation
Ummenhofer et al. (2009)
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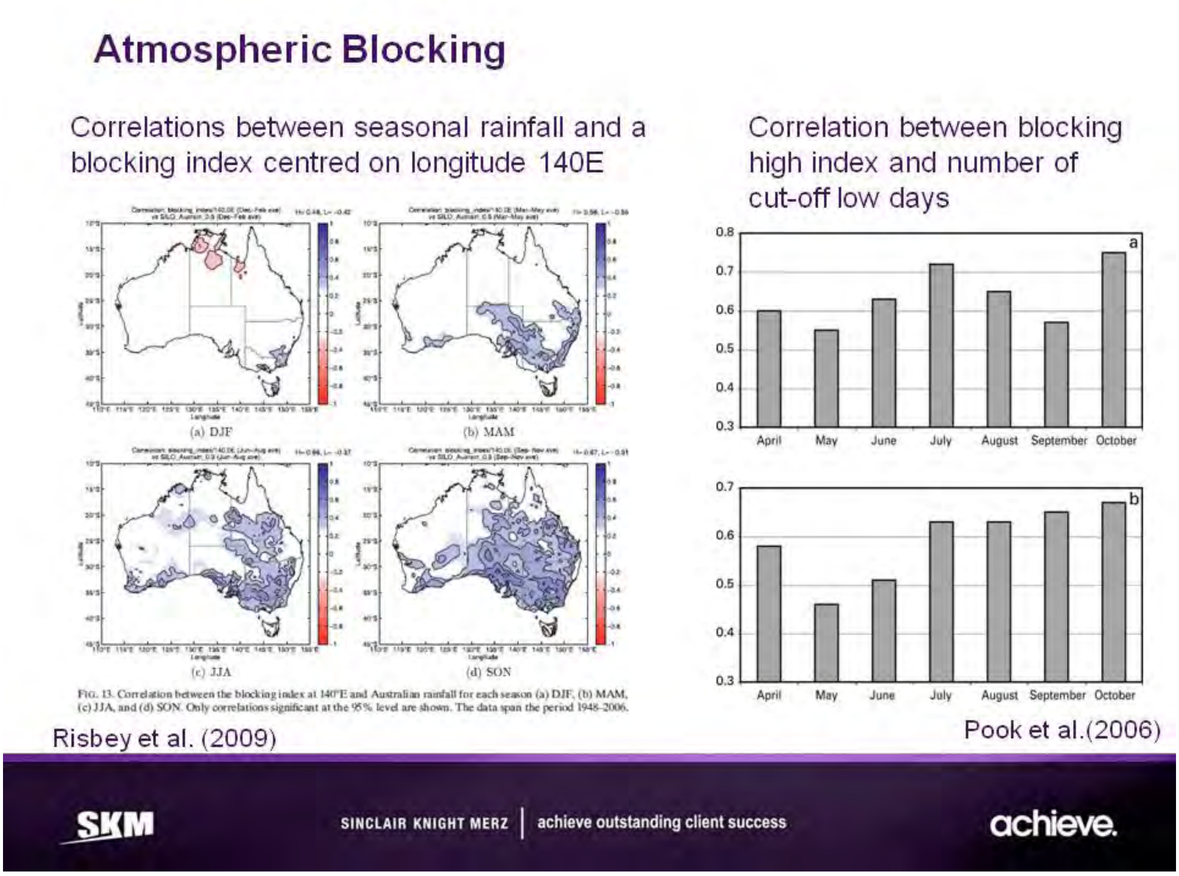
Atmospheric Blocking
Correlations between seasonal rainfall and a blocking index centred on longitude 140E
Correlation between blocking high index and number of cut-off low days
(a) DJF
(b) MAM
(c) JJA
(d) SON
FIG. 13. Correlation between the blocking index at 140°E and Australian rainfall for each season (a) DJF, (b) MAM, (c) JJA, and (d) SON. Only correlations significant at the 95% level are shown. The data span the period 1948-2006.
Risbey et al. (2009)
a
b
0.8
0.7
0.6
0.5
0.4
0.3
April
May
June
July
August
September
October
Pook et al.(2006)
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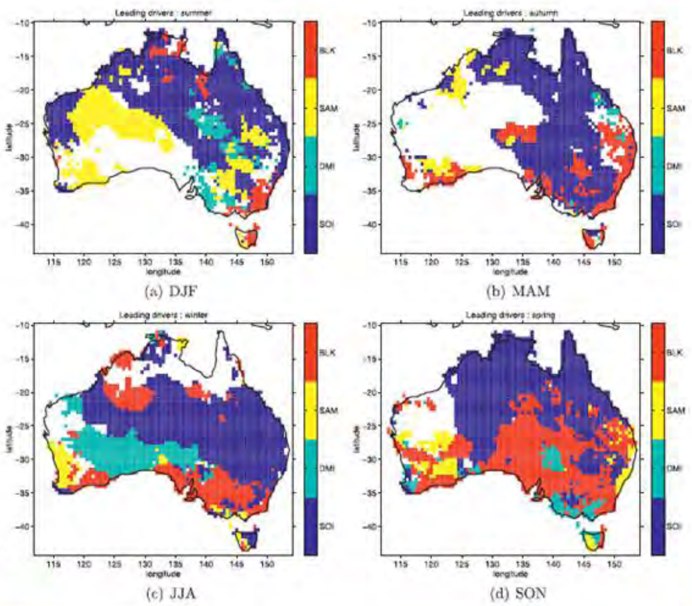
Dominant seasonal drivers



Risbey et al. (2009)

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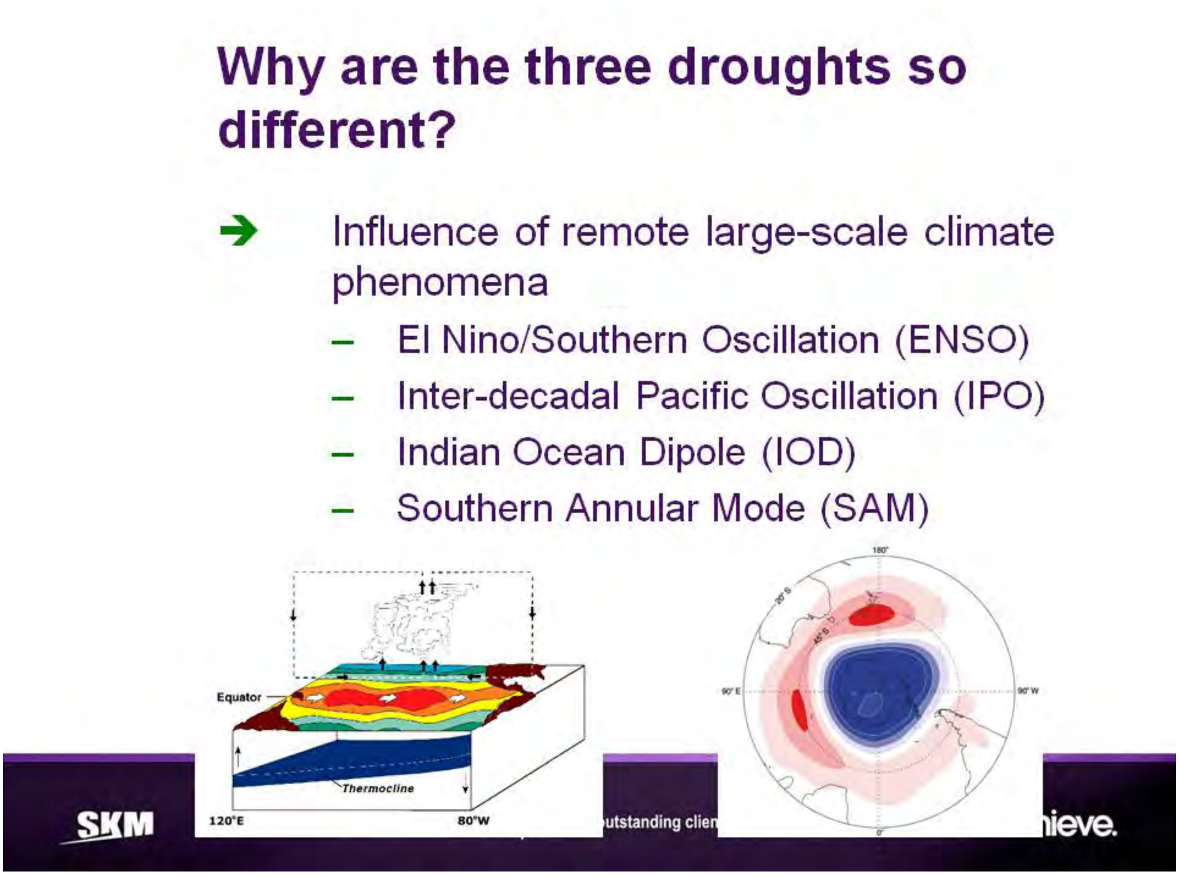
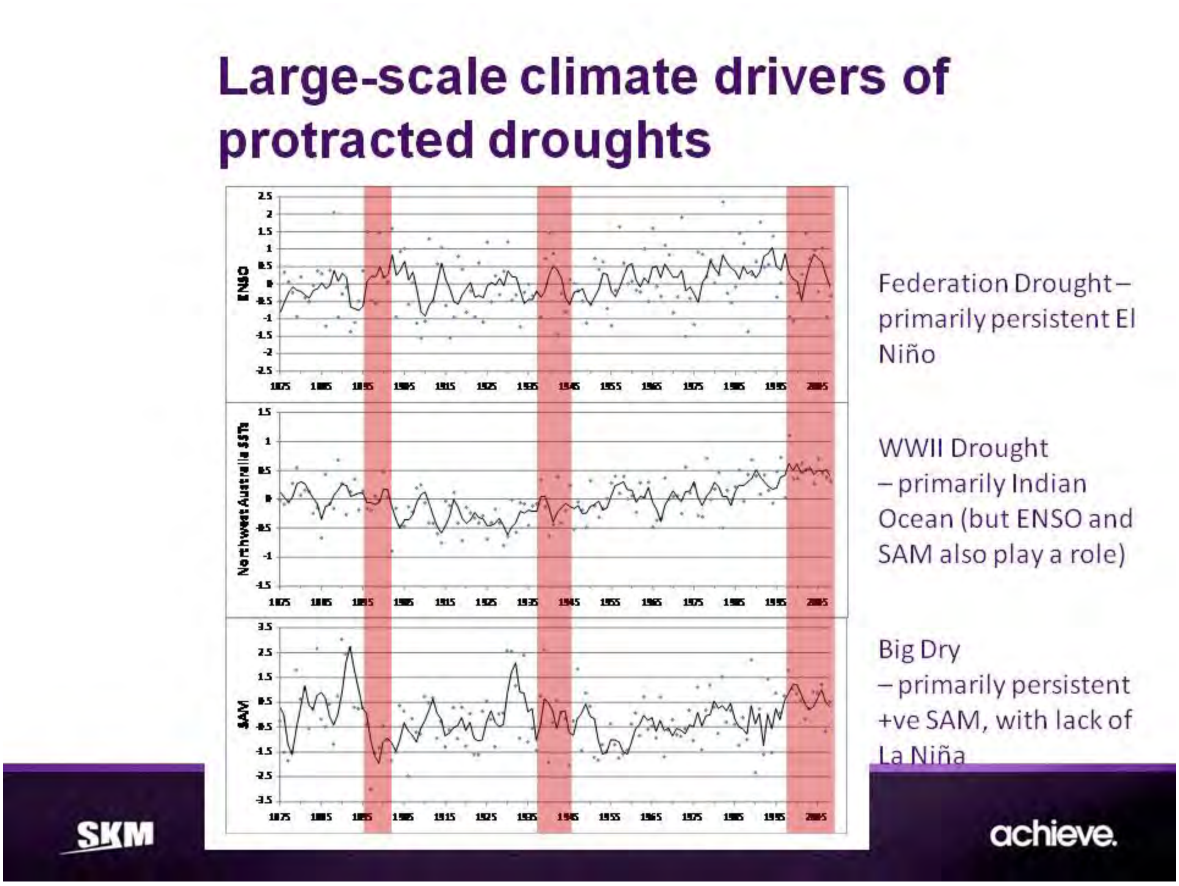

Why are the three droughts so different?
Influence of remote large-scale climate phenomena
– El Nino/Southern Oscillation (ENSO)
– Inter-decadal Pacific Oscillation (IPO)
– Indian Ocean Dipole (IOD)
– Southern Annular Mode (SAM)
Equator
Thermocline
120°E
80°W
SKM


Large-scale climate drivers of protracted droughts
ENSO
Northwest Australia SSTs
SAM
Federation Drought – primarily persistent El Niño
WWII Drought – primarily Indian Ocean (but ENSO and SAM also play a role)
Big Dry – primarily persistent +ve SAM, with lack of La Niña
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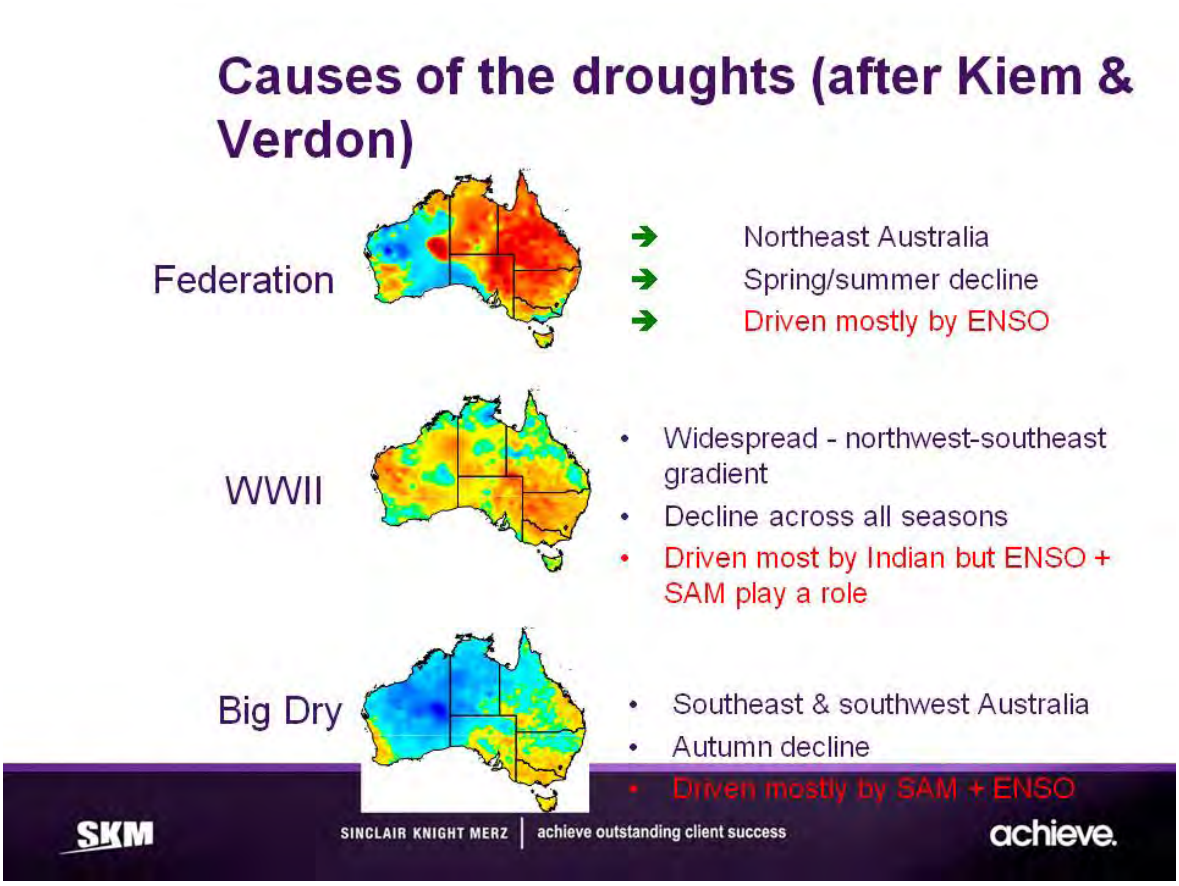
Causes of the droughts (after Kiem & Verdon)
Federation
Northeast Australia
Spring/summer decline
Driven mostly by ENSO
WWII
Widespread - northwest-southeast gradient
Decline across all seasons
Driven most by Indian but ENSO + SAM play a role
Big Dry
Southeast & southwest Australia
Autumn decline
Driven mostly by SAM + ENSO
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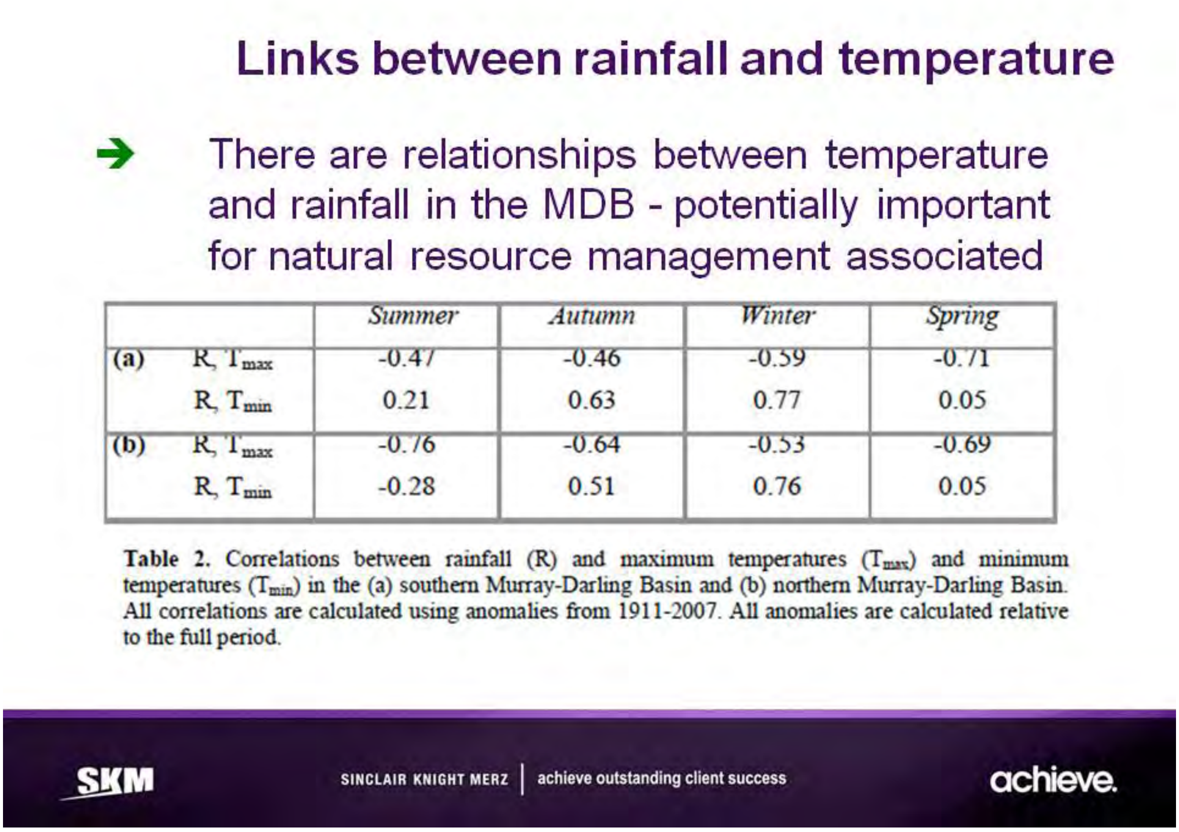
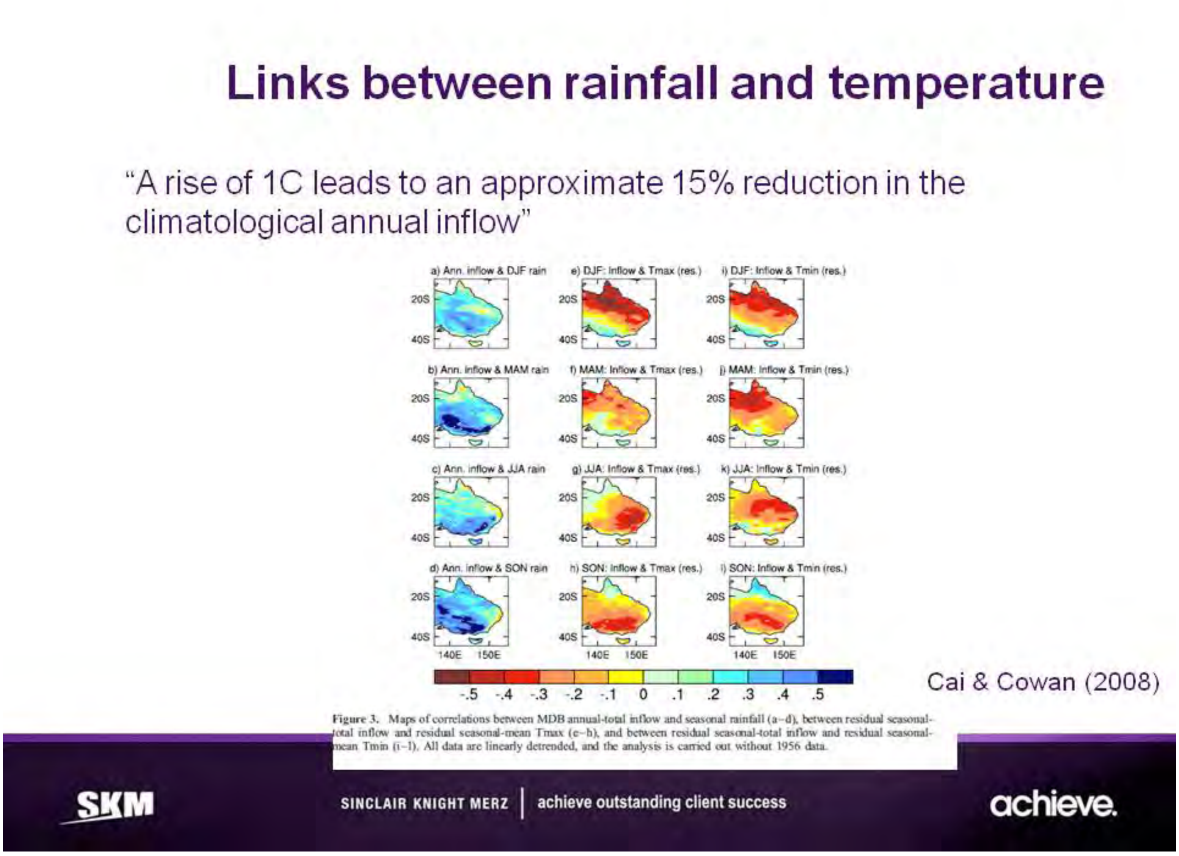


		Summer	*Autumn*	*Winter*	*Spring*
(a)	R, T_{max}	-0.47	-0.46	-0.59	-0.71
	R, T_{min}	0.21	0.63	0.77	0.05
(b)	R, T_{max}	-0.76	-0.64	-0.53	-0.69
	R, T_{min}	-0.28	0.51	0.76	0.05

Table 2. Correlations between rainfall (R) and maximum temperatures (T_{max}) and minimum temperatures (T_{min}) in the (a) southern Murray-Darling Basin and (b) northern Murray-Darling Basin. All correlations are calculated using anomalies from 1911-2007. All anomalies are calculated relative to the full period.


Links between rainfall and temperature
"A rise of 1C leads to an approximate 15% reduction in the climatological annual inflow"
a) Ann. inflow & DJF rain
e) DJF: Inflow & Tmax (res.)
i) DJF: Inflow & Tmin (res.)
b) Ann. inflow & MAM rain
f) MAM: Inflow & Tmax (res.)
j) MAM: Inflow & Tmin (res.)
c) Ann. inflow & JJA rain
g) JJA: Inflow & Tmax (res.)
k) JJA: Inflow & Tmin (res.)
d) Ann. inflow & SON rain
h) SON: Inflow & Tmax (res.)
l) SON: Inflow & Tmin (res.)
20S
40S
140E 150E
-.5 -.4 -.3 -.2 -.1 0 .1 .2 .3 .4 .5
Cai & Cowan (2008)
Figure 3. Maps of correlations between MDB annual-total inflow and seasonal rainfall (a–d), between residual seasonal-total inflow and residual seasonal-mean Tmax (e–h), and between residual seasonal-total inflow and residual seasonal-mean Tmin (i–l). All data are linearly detrended, and the analysis is carried out without 1956 data.
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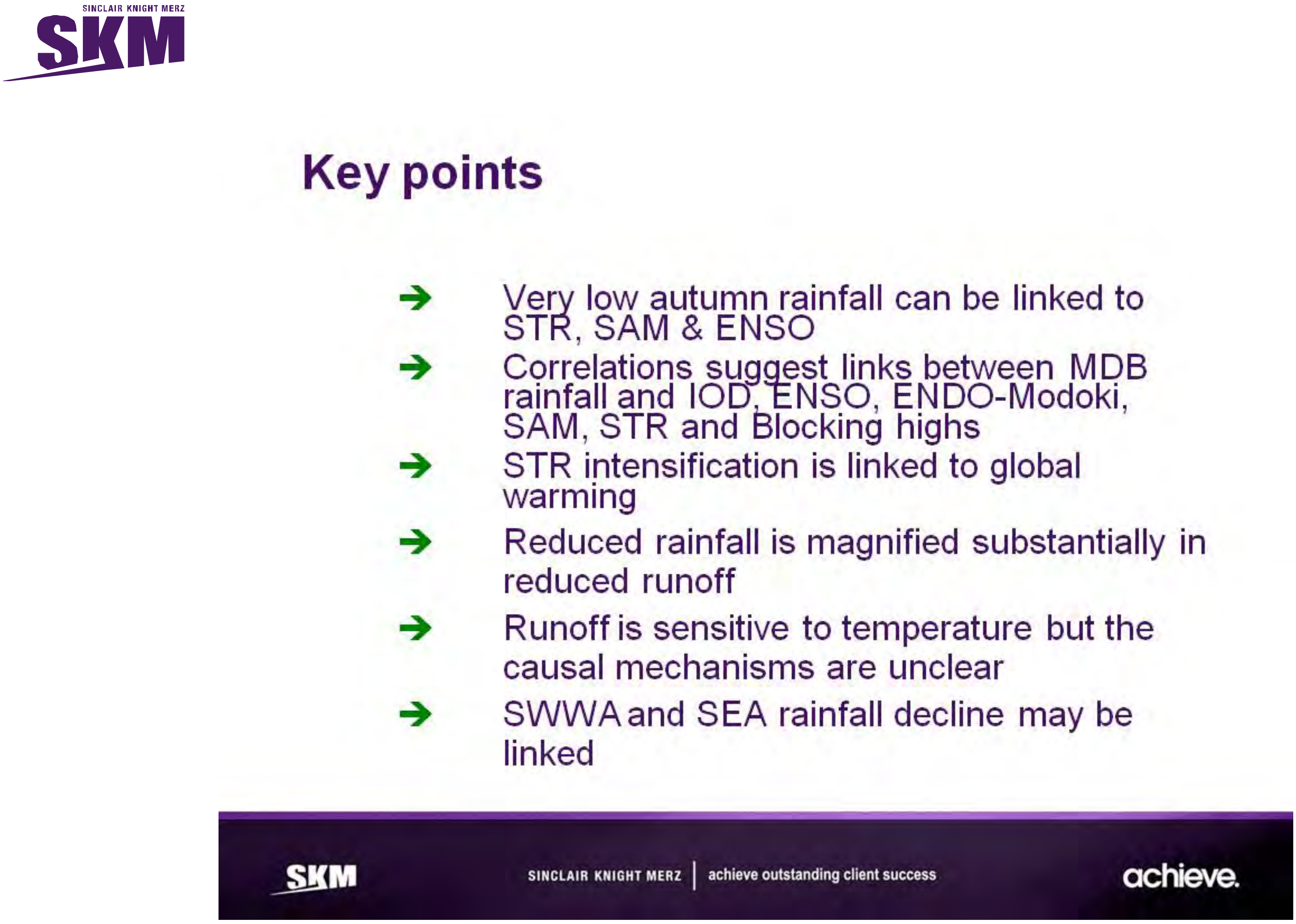
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Key points
Very low autumn rainfall can be linked to STR, SAM & ENSO
Correlations suggest links between MDB rainfall and IOD, ENSO, ENDO-Modoki, SAM, STR and Blocking highs
STR intensification is linked to global warming
Reduced rainfall is magnified substantially in reduced runoff
Runoff is sensitive to temperature but the causal mechanisms are unclear
SWWA and SEA rainfall decline may be linked
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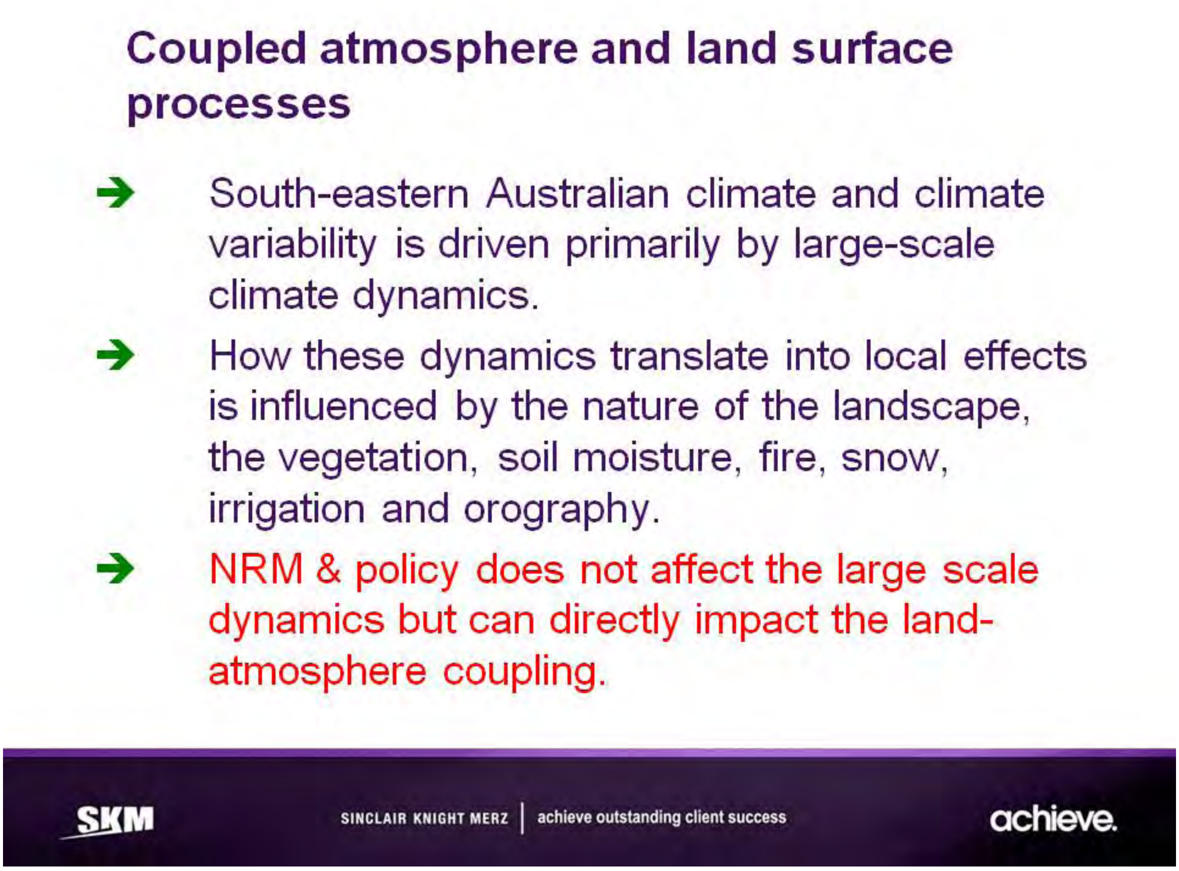
Coupled atmosphere and land surface processes
South-eastern Australian climate and climate variability is driven primarily by large-scale climate dynamics.
How these dynamics translate into local effects is influenced by the nature of the landscape, the vegetation, soil moisture, fire, snow, irrigation and orography.
NRM & policy does not affect the large scale dynamics but can directly impact the land-atmosphere coupling.
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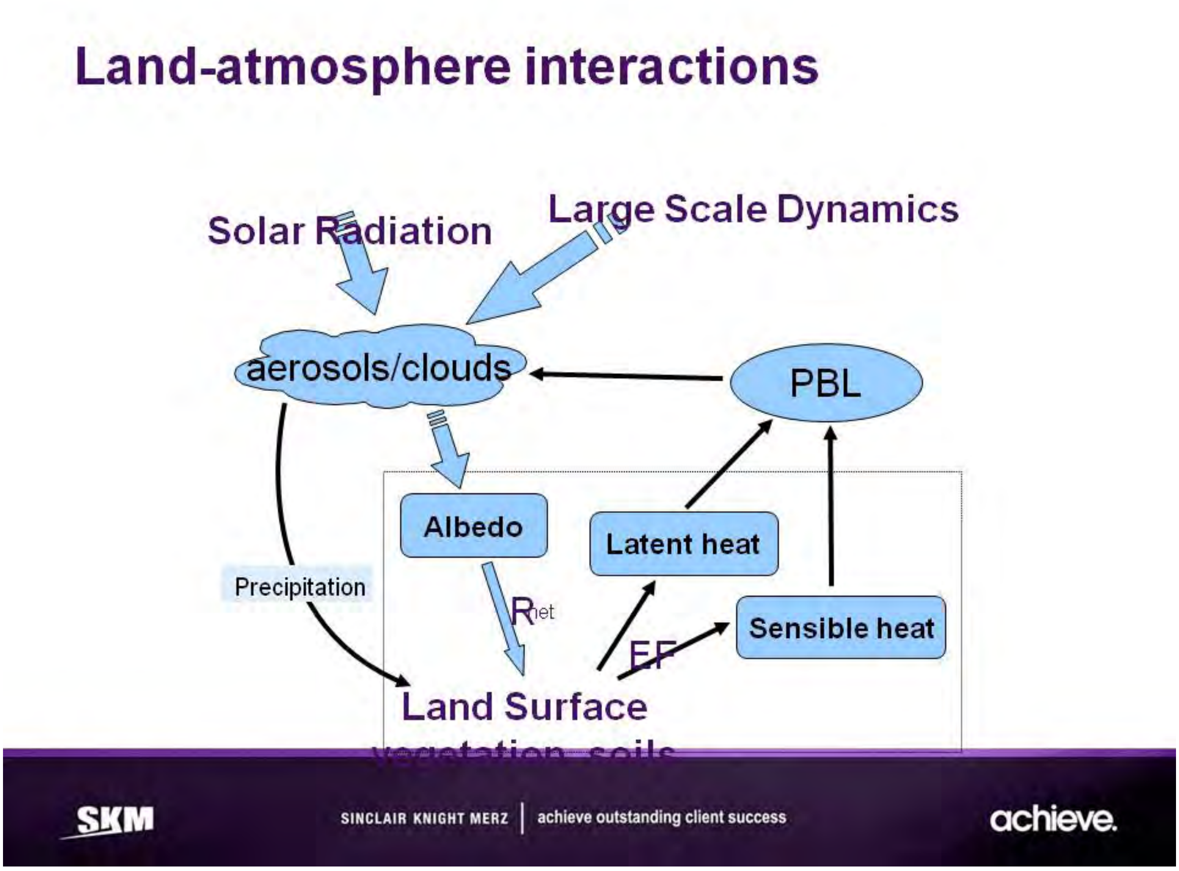
Land-atmosphere interactions
Solar Radiation
Large Scale Dynamics
aerosols/clouds
PBL
Albedo
Latent heat
Precipitation
Rnet
EF
Sensible heat
Land Surface
SKM
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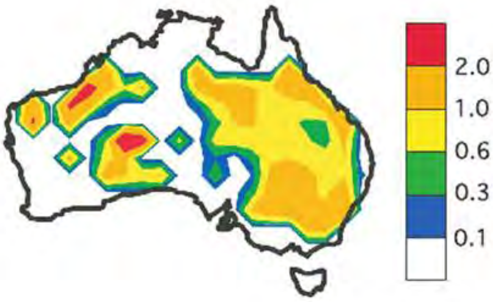
Soil moisture feedback estimates



- Mean December, January, February soil moisture feedback (on precipitation) parameter among 19 IPCC models.
- Notaro, M. (2008), Statistical identification of global hot spots in soil moisture feedbacks among IPCC AR4 models, J. Geophys. Res., 113, D09101, doi:10.1029/2007JD009199.

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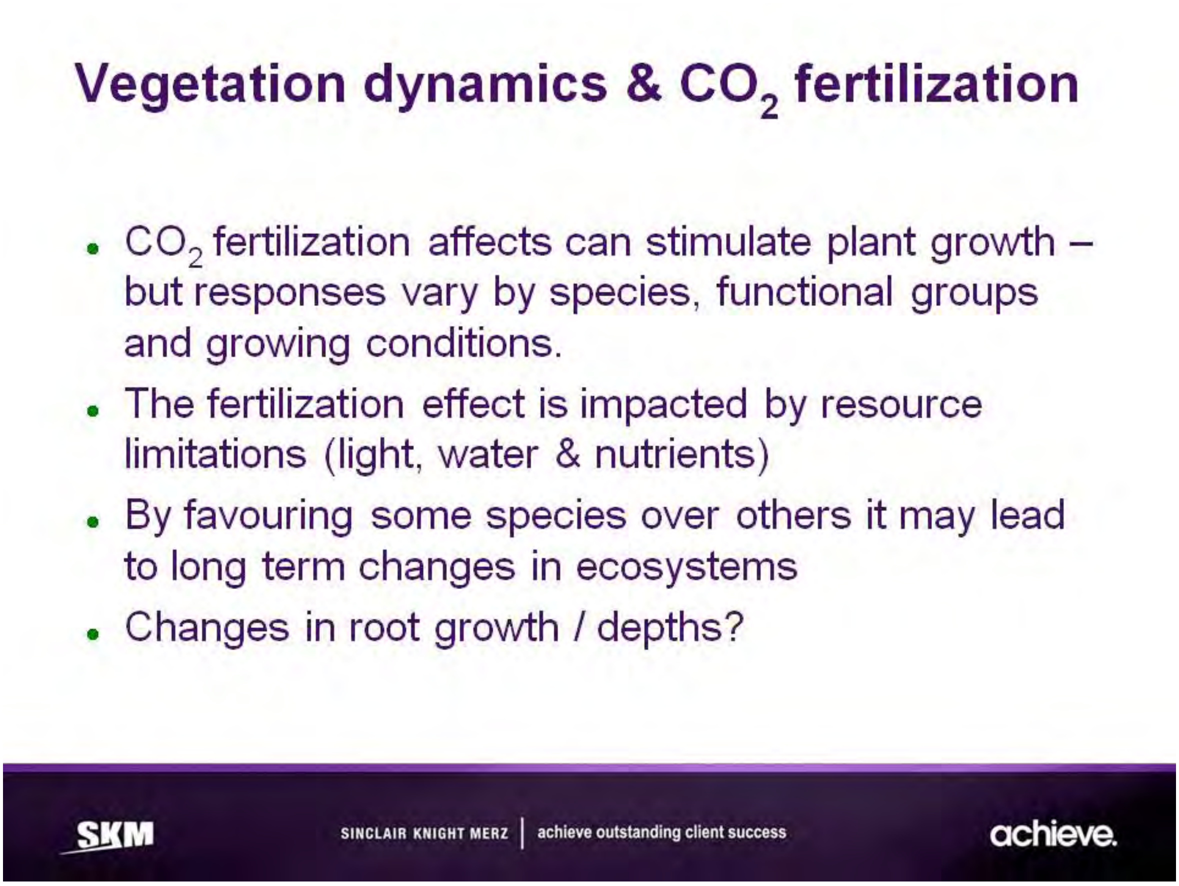

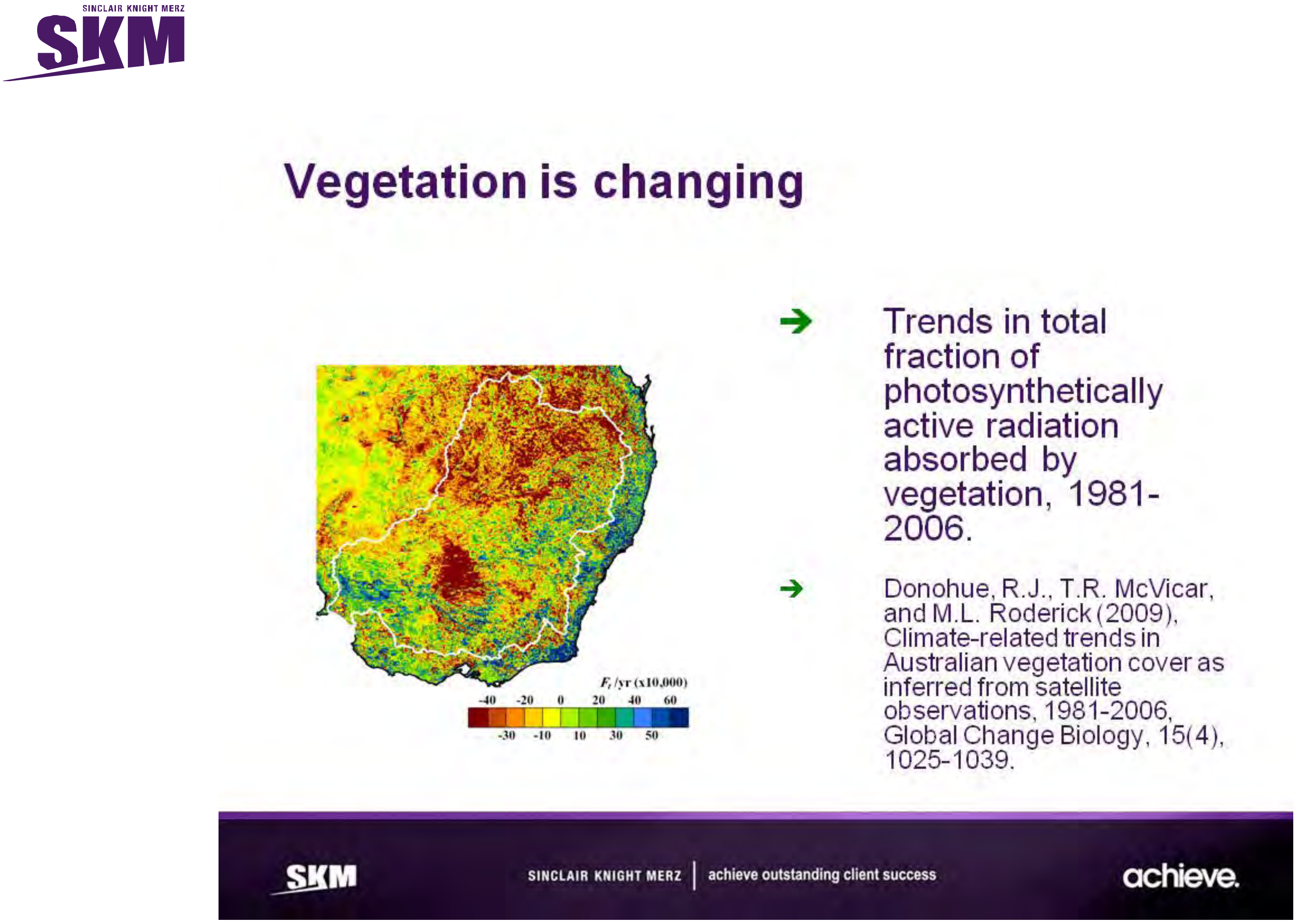
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Vegetation is changing
Trends in total fraction of photosynthetically active radiation absorbed by vegetation, 1981-2006.
Donohue, R.J., T.R. McVicar, and M.L. Roderick (2009), Climate-related trends in Australian vegetation cover as inferred from satellite observations, 1981-2006, Global Change Biology, 15(4), 1025-1039.
Ft /yr (x10,000)
-40 -20 0 20 40 60
-30 -10 10 30 50
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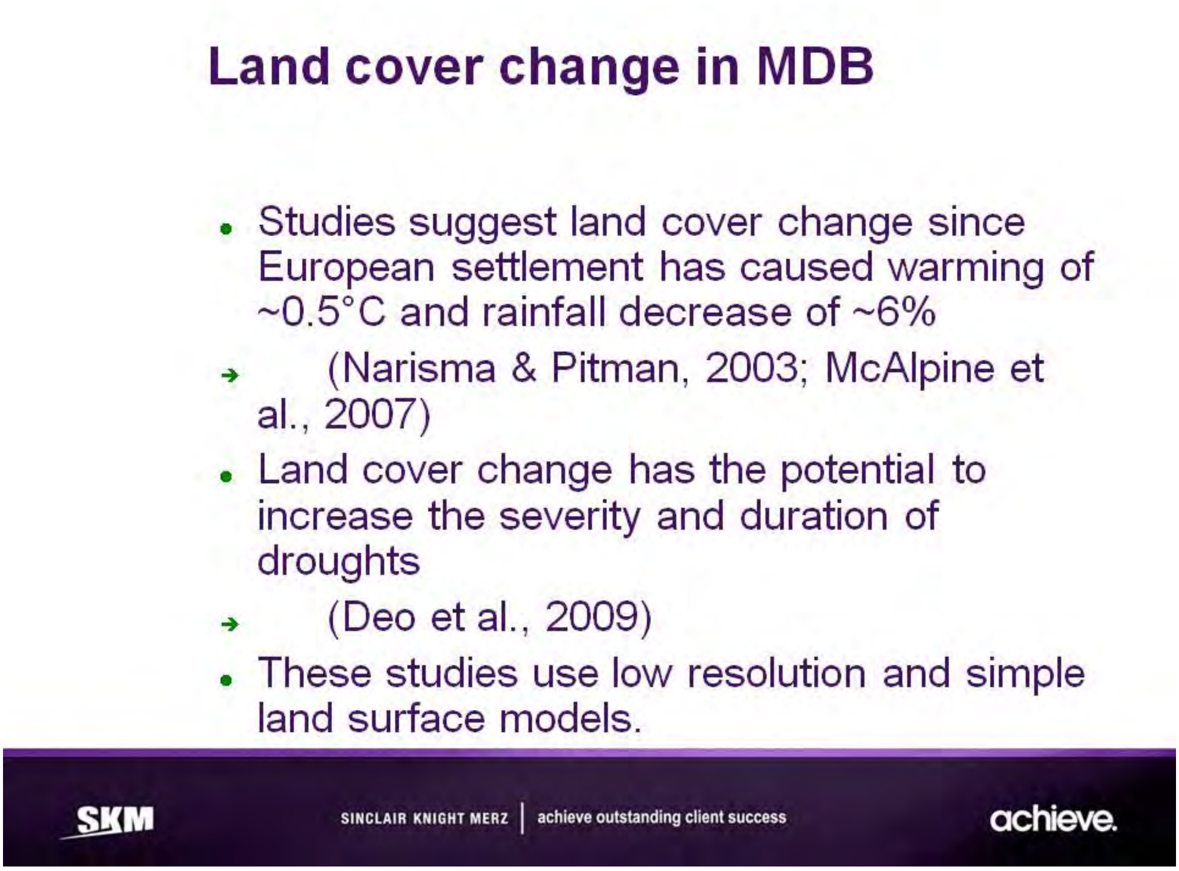
Land cover change in MDB
Studies suggest land cover change since European settlement has caused warming of ~0.5°C and rainfall decrease of ~6%
(Narisma & Pitman, 2003; McAlpine et al., 2007)
Land cover change has the potential to increase the severity and duration of droughts
(Deo et al., 2009)
These studies use low resolution and simple land surface models.
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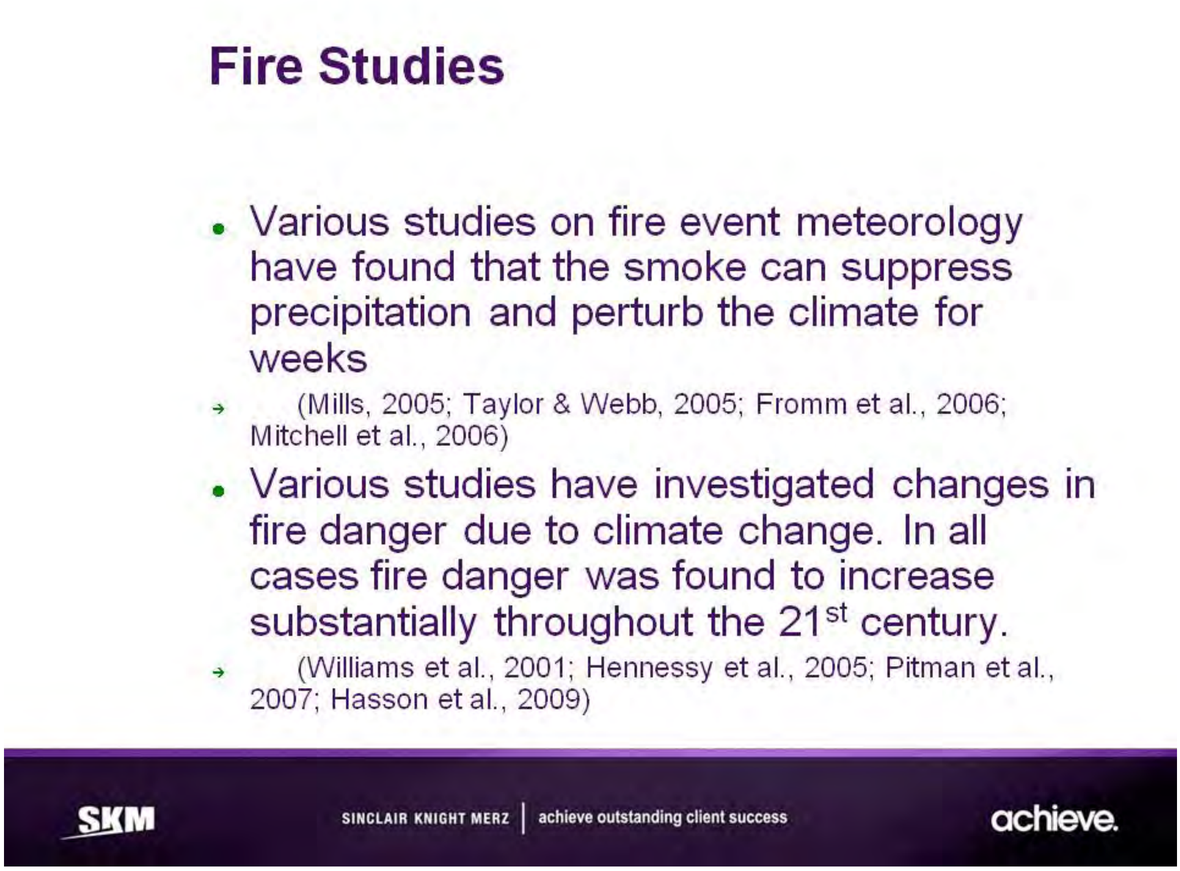
Fire Studies
Various studies on fire event meteorology have found that the smoke can suppress precipitation and perturb the climate for weeks
(Mills, 2005; Taylor & Webb, 2005; Fromm et al., 2006; Mitchell et al., 2006)
Various studies have investigated changes in fire danger due to climate change. In all cases fire danger was found to increase substantially throughout the 21st century.
(Williams et al., 2001; Hennessy et al., 2005; Pitman et al., 2007; Hasson et al., 2009)
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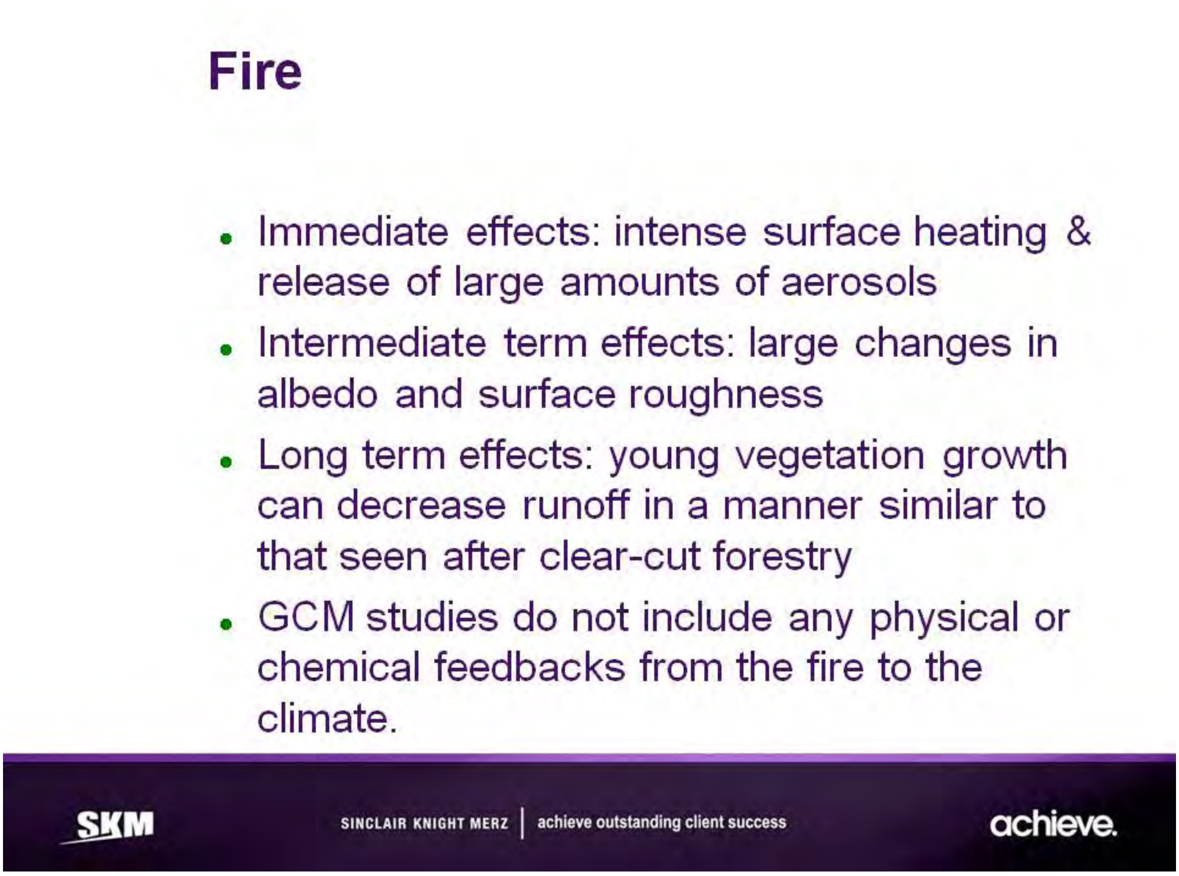
Fire
Immediate effects: intense surface heating & release of large amounts of aerosols
Intermediate term effects: large changes in albedo and surface roughness
Long term effects: young vegetation growth can decrease runoff in a manner similar to that seen after clear-cut forestry
GCM studies do not include any physical or chemical feedbacks from the fire to the climate.
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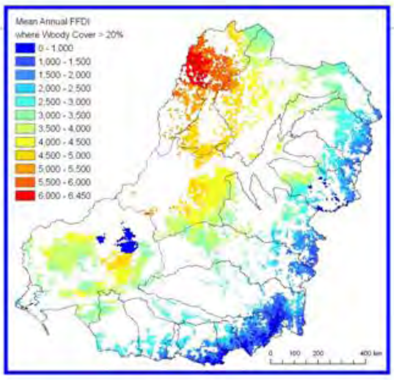
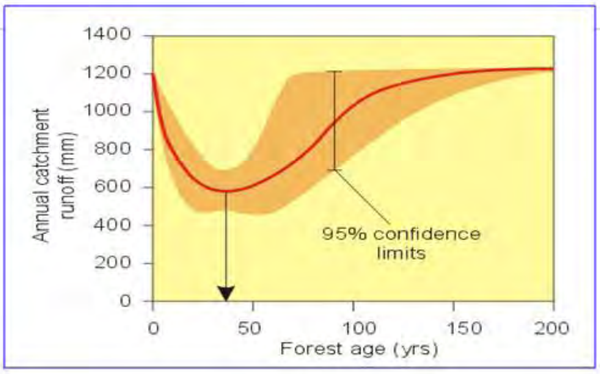
Bushfire impact on streamflow





- Forest fire danger index (FFDI) is predicted to increase due to climate change
- Changes in runoff following bushfires can be estimated using Kuczera's curve.
- It works well for mountain ash, but not very well for other species.

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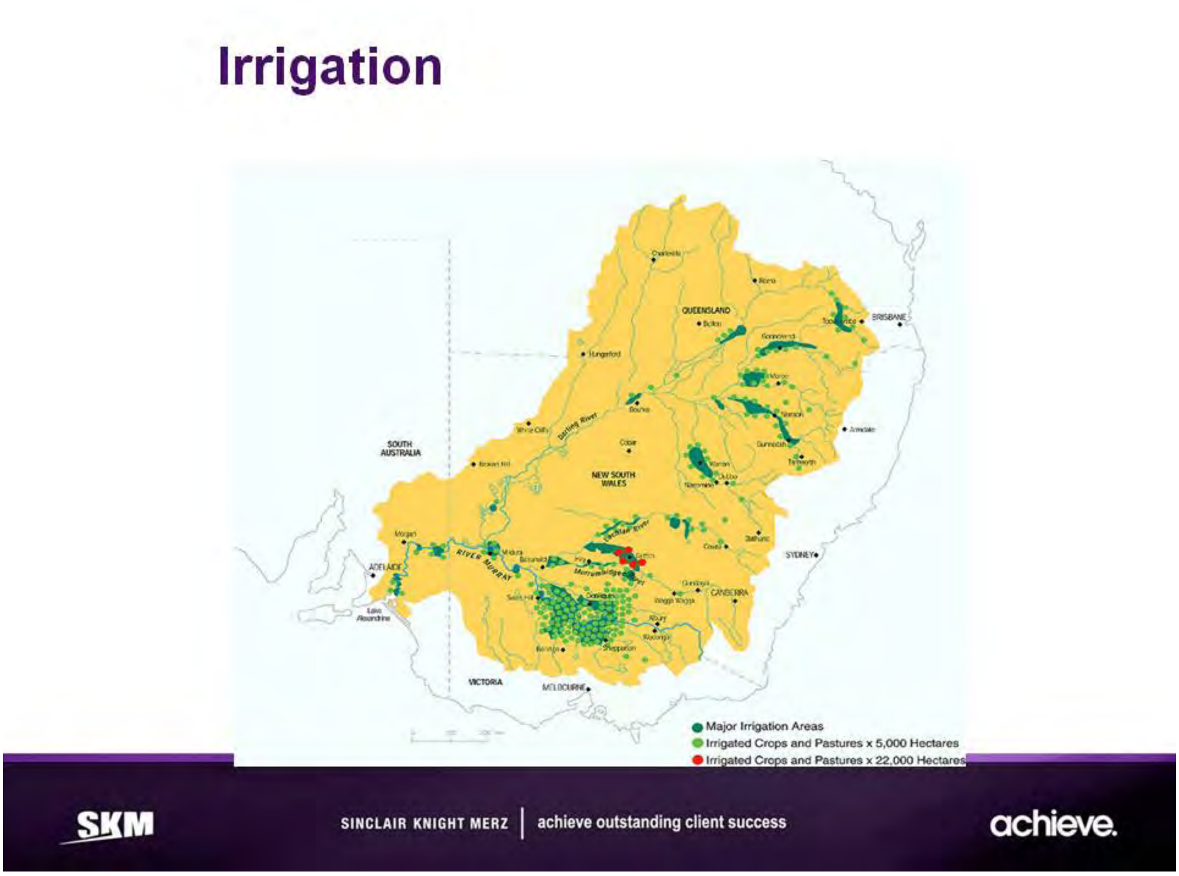
Irrigation
QUEENSLAND
NEW SOUTH WALES
SOUTH AUSTRALIA
VICTORIA
BRISBANE
SYDNEY
CANBERRA
MELBOURNE
ADELAIDE
Major Irrigation Areas
Irrigated Crops and Pastures x 5,000 Hectares
Irrigated Crops and Pastures x 22,000 Hectares
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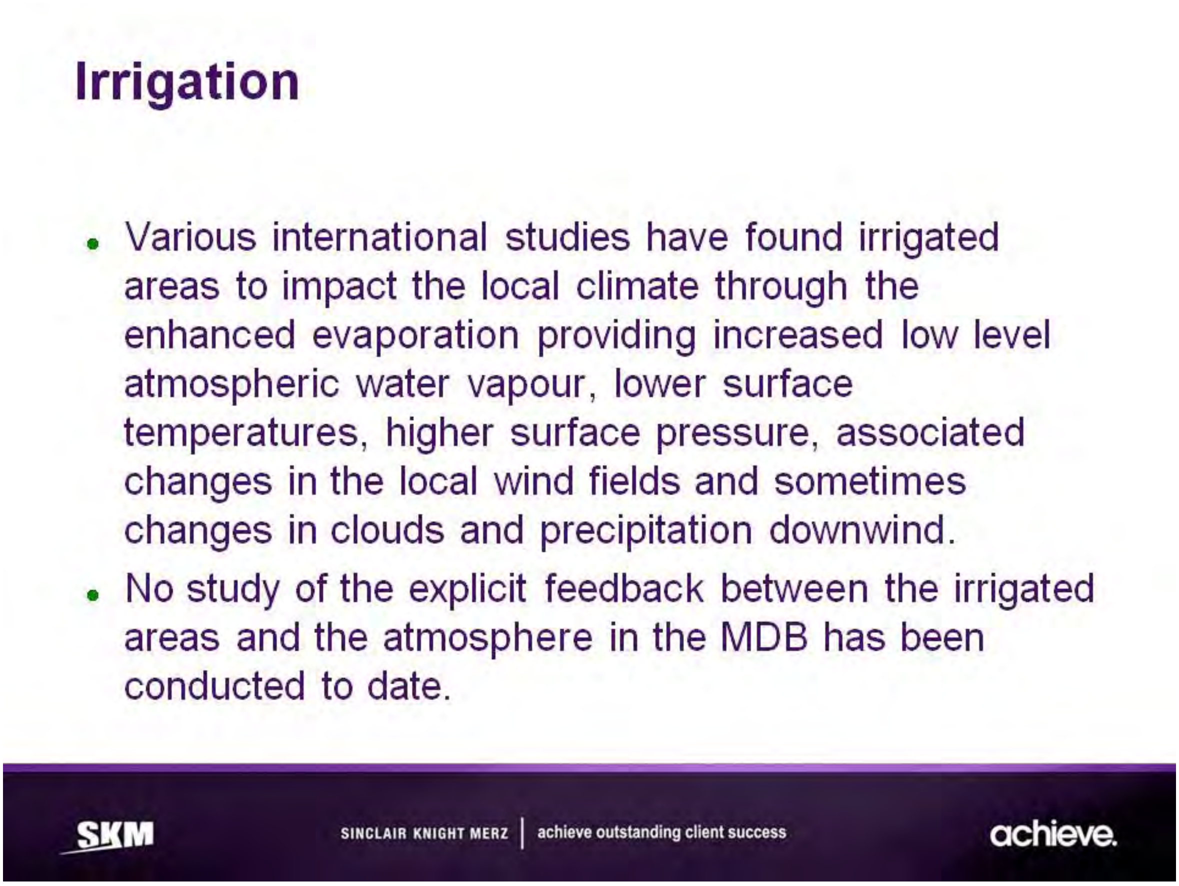
Irrigation
Various international studies have found irrigated areas to impact the local climate through the enhanced evaporation providing increased low level atmospheric water vapour, lower surface temperatures, higher surface pressure, associated changes in the local wind fields and sometimes changes in clouds and precipitation downwind.
No study of the explicit feedback between the irrigated areas and the atmosphere in the MDB has been conducted to date.
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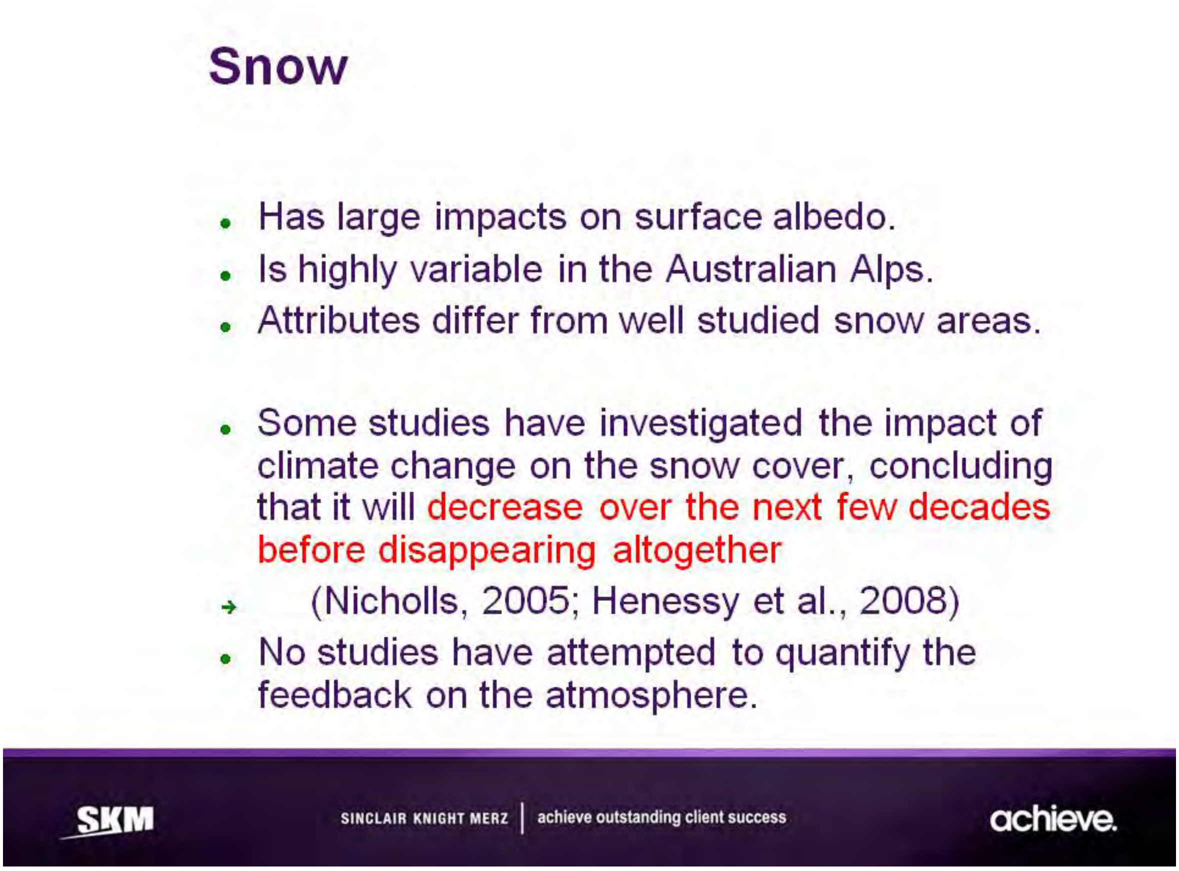
Snow
Has large impacts on surface albedo.
Is highly variable in the Australian Alps.
Attributes differ from well studied snow areas.
Some studies have investigated the impact of climate change on the snow cover, concluding that it will decrease over the next few decades before disappearing altogether
(Nicholls, 2005; Henessy et al., 2008)
No studies have attempted to quantify the feedback on the atmosphere.
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Predictions

- Temperature
- Rainfall
- Runoff

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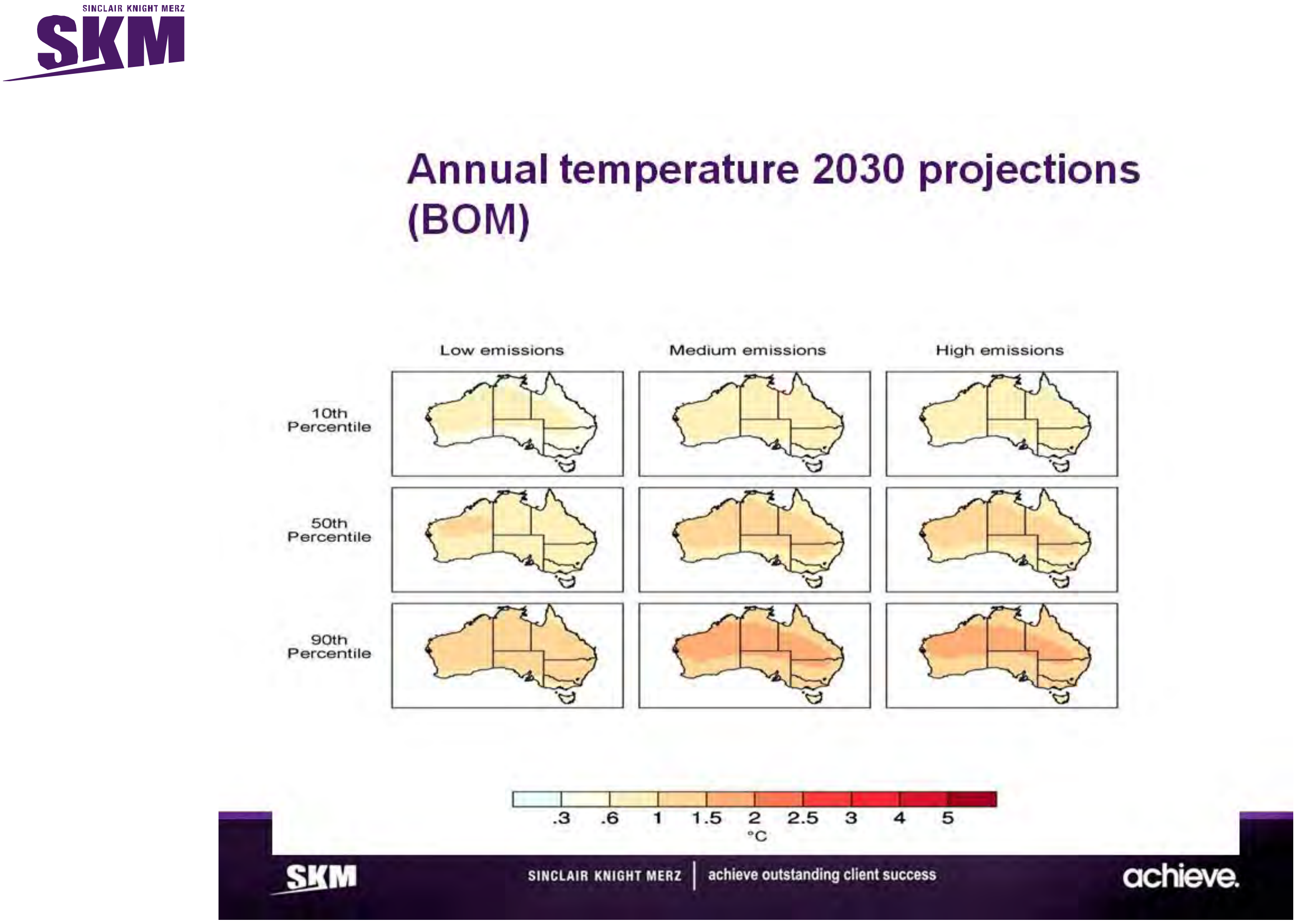
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Annual temperature 2030 projections (BOM)
Low emissions
Medium emissions
High emissions
10th Percentile
50th Percentile
90th Percentile
.3 .6 1 1.5 2 2.5 3 4 5
°C
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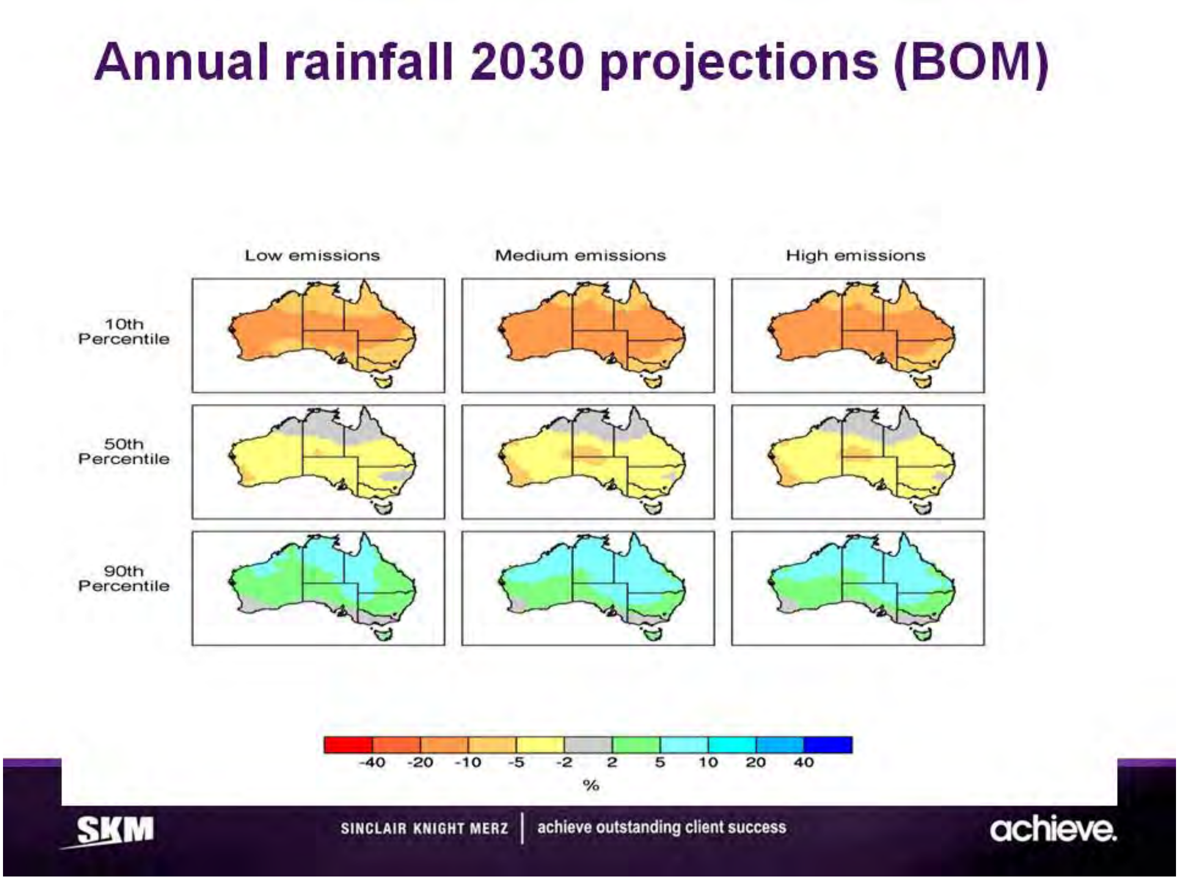
Annual rainfall 2030 projections (BOM)
Low emissions
Medium emissions
High emissions
10th Percentile
50th Percentile
90th Percentile
-40 -20 -10 -5 -2 2 5 10 20 40
%
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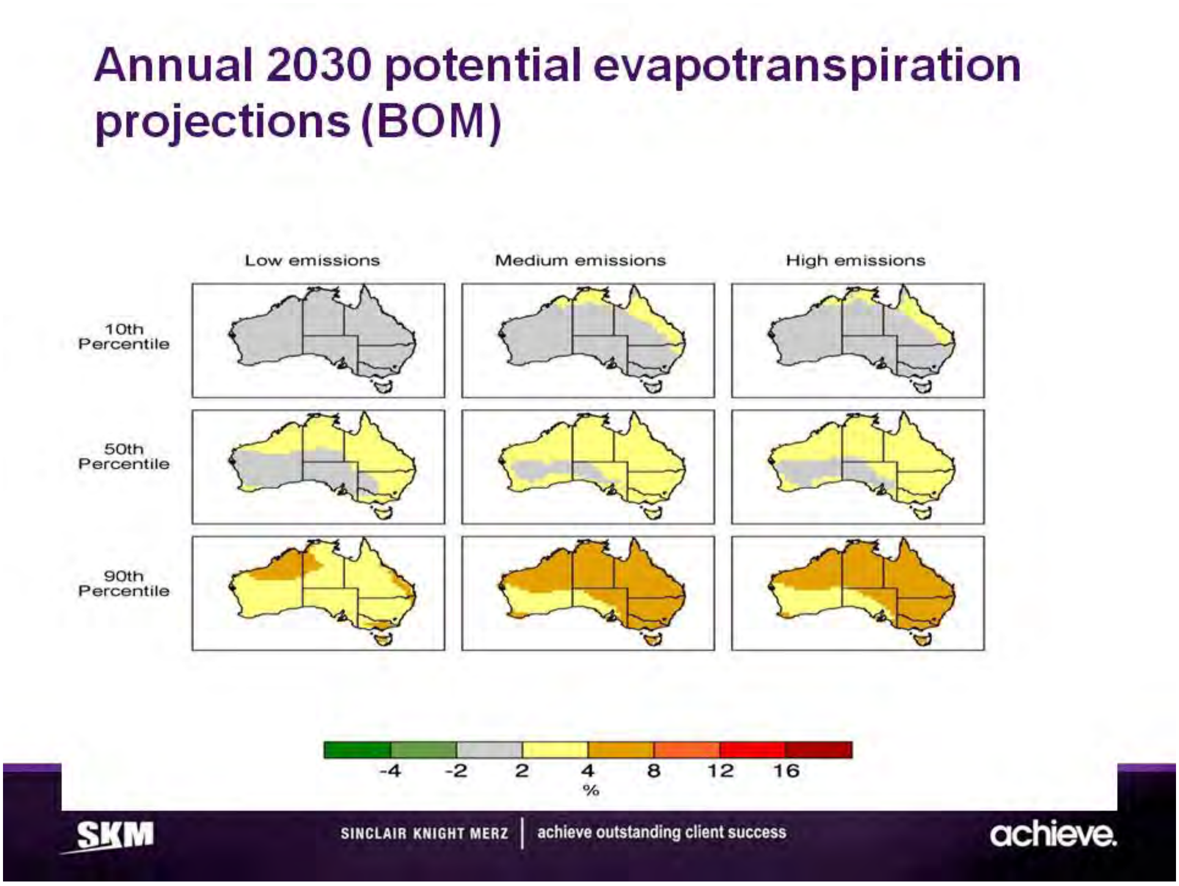
Annual 2030 potential evapotranspiration projections (BOM)
Low emissions
Medium emissions
High emissions
10th Percentile
50th Percentile
90th Percentile
-4
-2
2
4
8
12
16
%
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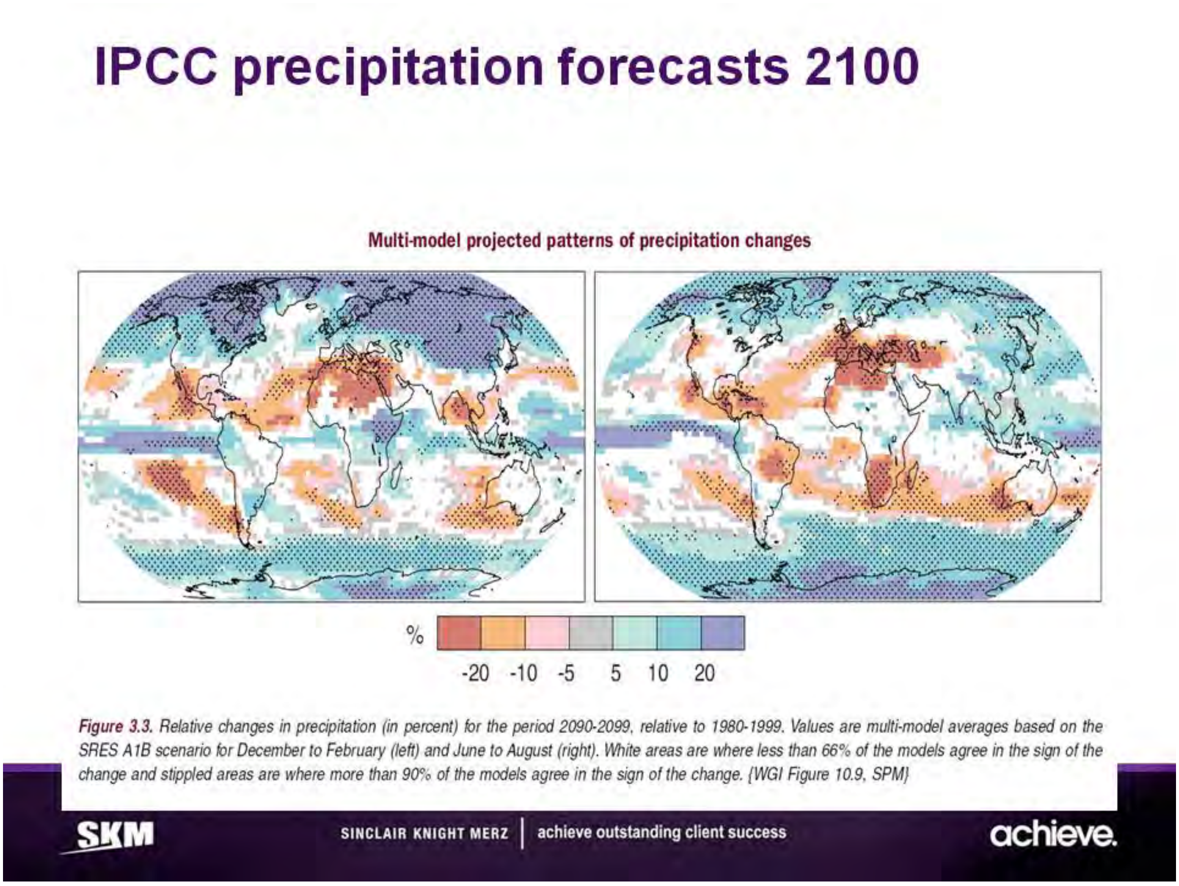
IPCC precipitation forecasts 2100
Multi-model projected patterns of precipitation changes
%
-20 -10 -5 5 10 20
Figure 3.3. Relative changes in precipitation (in percent) for the period 2090-2099, relative to 1980-1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. {WGI Figure 10.9, SPM}
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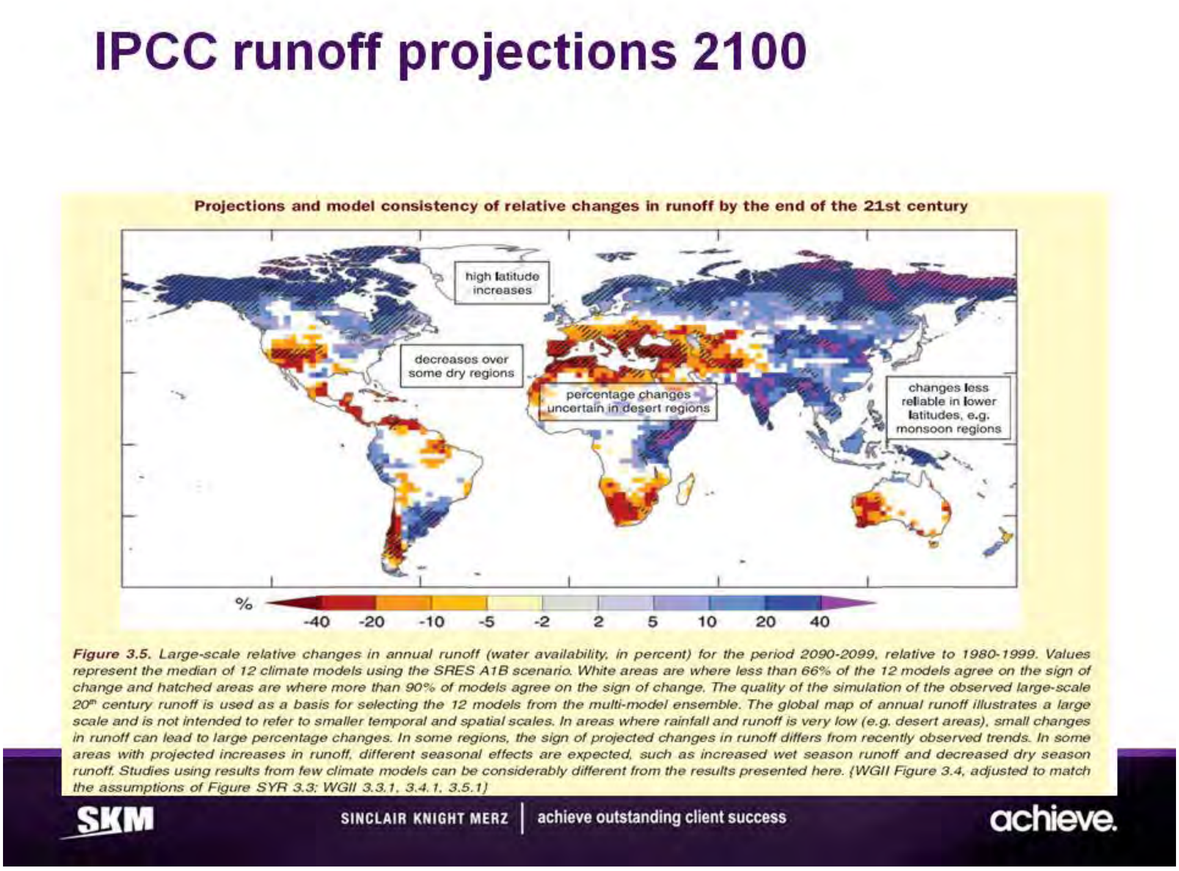

Figure 3.5. *Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change. The quality of the simulation of the observed large-scale 20th century runoff is used as a basis for selecting the 12 models from the multi-model ensemble. The global map of annual runoff illustrates a large scale and is not intended to refer to smaller temporal and spatial scales. In areas where rainfall and runoff is very low (e.g. desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends. In some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet season runoff and decreased dry season runoff. Studies using results from few climate models can be considerably different from the results presented here. {WGII Figure 3.4, adjusted to match the assumptions of Figure SYR 3.3; WGII 3.3.1, 3.4.1, 3.5.1}*

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MDBSYP scenarios

- The historical climate scenario (Scenario A) is the baseline against which other scenarios are compared. It is based on observed SILO Data Drill climate data from 1895 to 2006.
- The recent climate scenario (Scenario B) is used to assess future water availability should the climate in the future prove to be similar to that of the last ten years. Climate data for 1997 to 2006 are used to generate stochastic replicates of 112-year daily climate sequences. The replicate which produces a mean annual runoff closest to that observed in 1997 to 2006 is selected to define this scenario.
- The future climate scenario (Scenario C) is used to assess the range of likely climate conditions around the year 2030. Forty-five future climate variants, each with 112 years of daily climate sequences, are used. The future climate variants come from scaling the 1895 to 2006 climate data to represent ~2030 climate, based on analyses of 15 global climate models (GCMs) and three global warming scenarios from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4).

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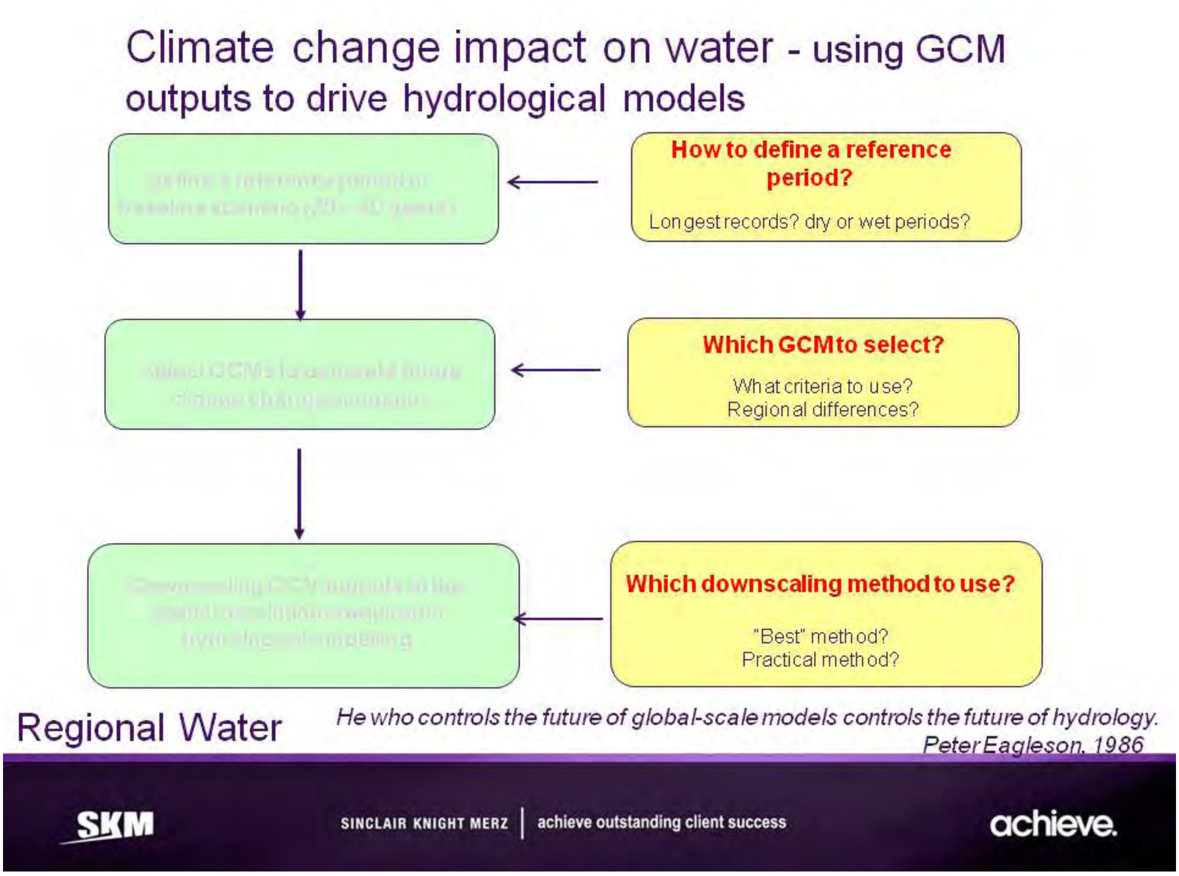
Climate change impact on water - using GCM outputs to drive hydrological models
How to define a reference period?
Longest records? dry or wet periods?
Which GCM to select?
What criteria to use?
Regional differences?
Which downscaling method to use?
"Best" method?
Practical method?
Regional Water
He who controls the future of global-scale models controls the future of hydrology.
Peter Eagleson, 1986
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Hydrological scaling method in MDBSYP

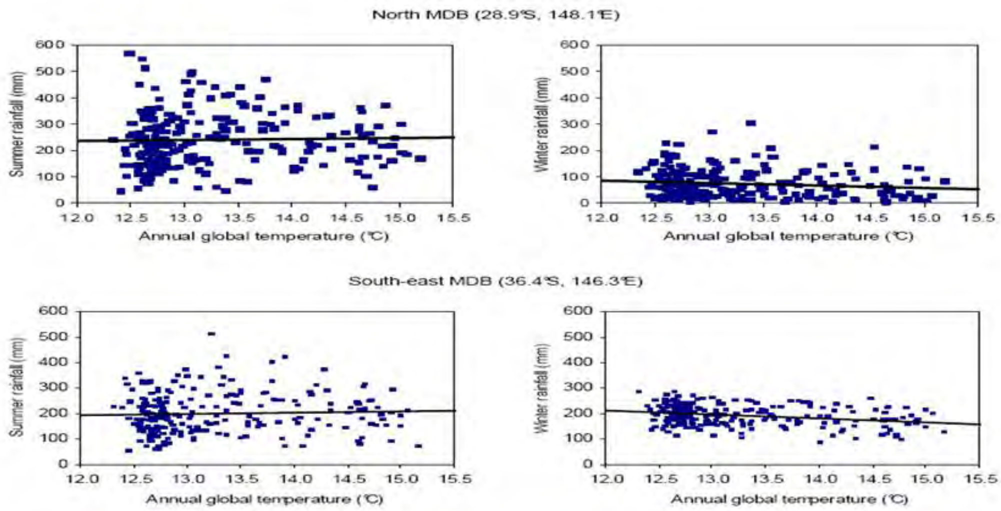

Figure 4-2 Example plots showing method used to estimate change in rainfall per degree global warming (Plots show summer (DJF) and winter (JJA) rainfall versus global average temperature from CSIRO-MK3.0 GCM simulations for 1895 to 2100 for two selected GCM grids in the MDB, with the slope of the regression line giving the rainfall change per degree global warming)

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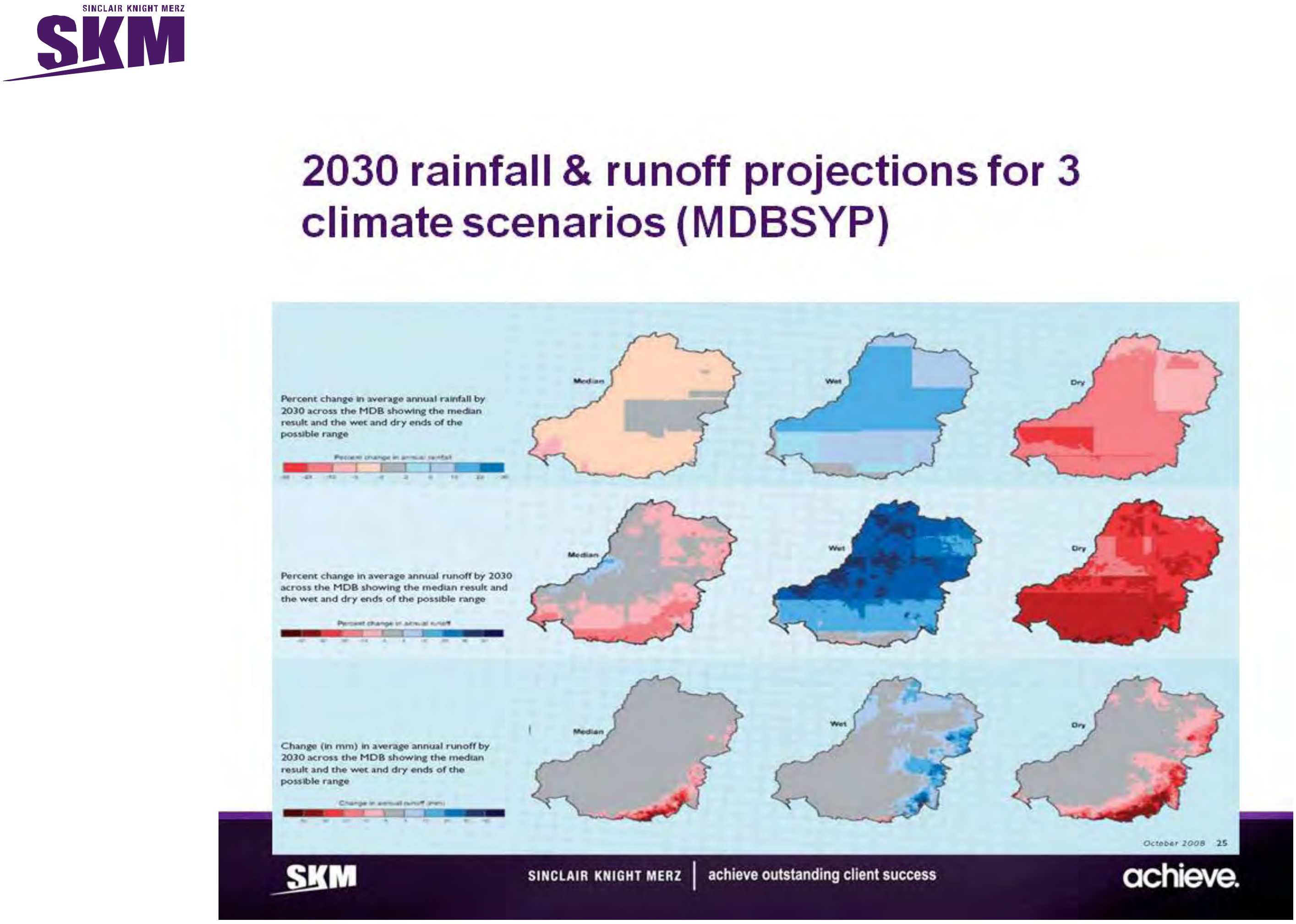
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2030 rainfall & runoff projections for 3 climate scenarios (MDBSYP)
Percent change in average annual rainfall by 2030 across the MDB showing the median result and the wet and dry ends of the possible range
Median
Wet
Dry
Percent change in average annual runoff by 2030 across the MDB showing the median result and the wet and dry ends of the possible range
Median
Wet
Dry
Change (in mm) in average annual runoff by 2030 across the MDB showing the median result and the wet and dry ends of the possible range
Median
Wet
Dry
October 2008 25
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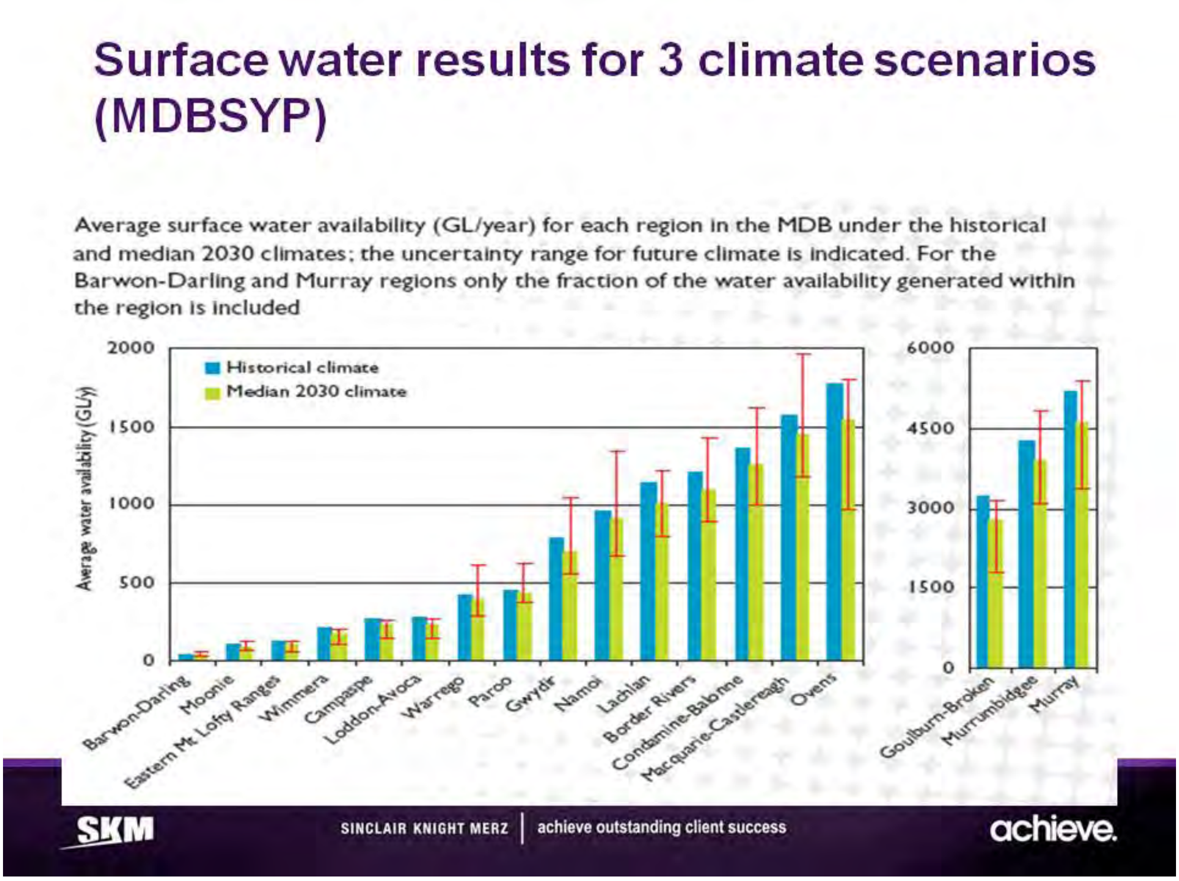
Surface water results for 3 climate scenarios (MDBSYP)
Average surface water availability (GL/year) for each region in the MDB under the historical and median 2030 climates; the uncertainty range for future climate is indicated. For the Barwon-Darling and Murray regions only the fraction of the water availability generated within the region is included
Historical climate
Median 2030 climate
Average water availability (GL/y)
2000
1500
1000
500
0
6000
4500
3000
1500
0
Barwon-Darling
Moonie
Eastern Mt Lofty Ranges
Wimmera
Campaspe
Loddon-Avoca
Warrego
Paroo
Gwydir
Namoi
Lachlan
Border Rivers
Condamine-Balonne
Macquarie-Castlereagh
Ovens
Goulburn-Broken
Murrumbidgee
Murray
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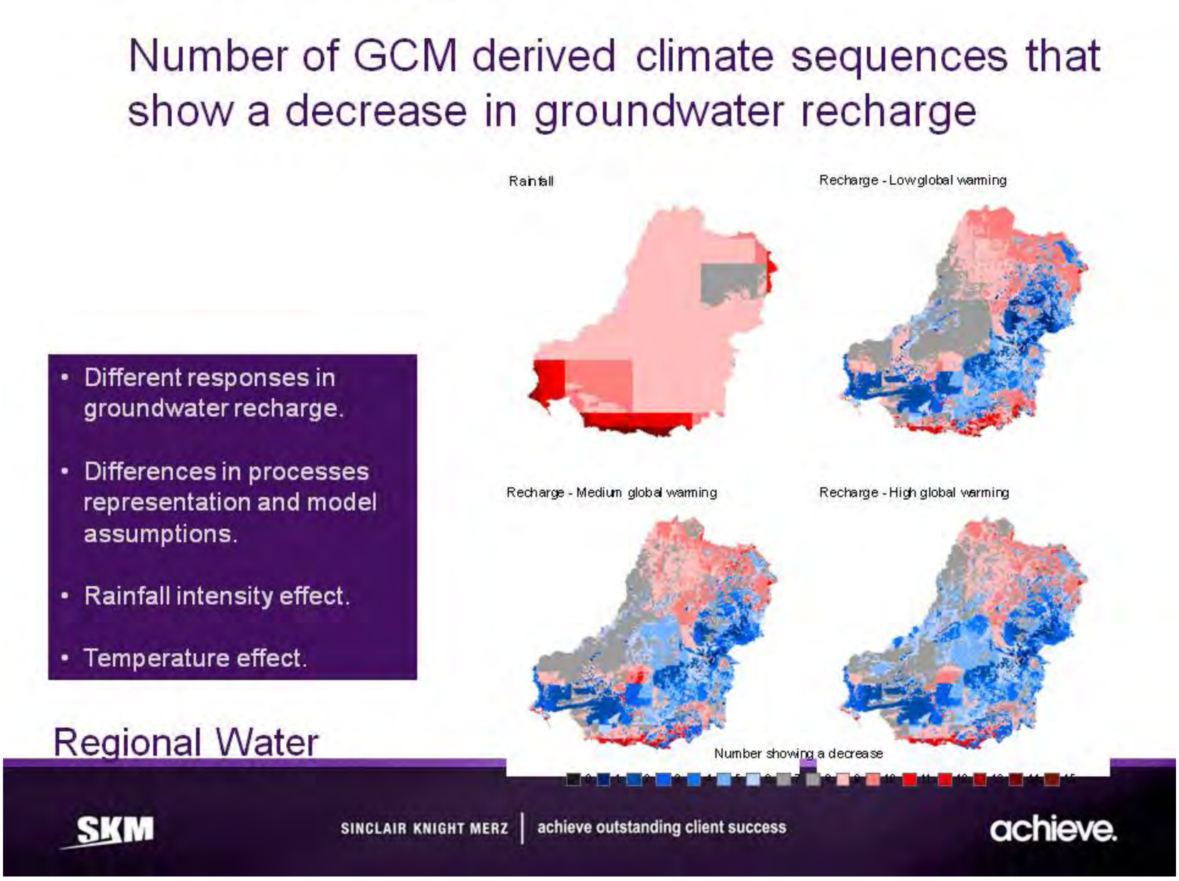

Number of GCM derived climate sequences that show a decrease in groundwater recharge
Rainfall
Recharge - Low global warming
Recharge - Medium global warming
Recharge - High global warming
Number showing a decrease
• Different responses in groundwater recharge.
• Differences in processes representation and model assumptions.
• Rainfall intensity effect.
• Temperature effect.
Regional Water
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MDBSYP scenarios issues

- Hydrological simulations rely on climate inputs. Hence the model outputs are only as good as the climate inputs
- The15 GCMs give very different results (model uncertainty) due to their inclusion/representation of different processes
- The GCMs currently have poor resolution at the MDB spatial scale
- The GCMs use SRES emission scenarios - current emissions are higher than the SRES (2000) worst case
- The CSIRO MDBSYP CC scenarios do not take into account the main drivers of **climate variability** in the MDB (e.g. ENSO, ENSO-Modoki, SAM, STR, IOD, Blocking Highs)
- The GCMs do not include surface-atmosphere feedbacks
- The 1895-2006 baseline includes a significant amount of land use change that itself affects the climate.

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MDBSYP scenarios issues

- The 'historical instrumental record' already incorporates a significant amount of CC impact
- Seasonal GCM rainfall projections disagree with observations
- They may have a timing issue if indeed CC impacts are already somewhat stronger than GCMs suggest
- The hydrology models scale historical data (based on correlations with future temperature projections) – hence do not represent any temporal change in the time series
- The climate-hydrology models do not represent many of the CC features of interest
- The 1895-2006 baseline does not account for the full range of natural climate variability (ie without CC). Palaeo-evidence for example shows severe droughts lasting up to 50 years.

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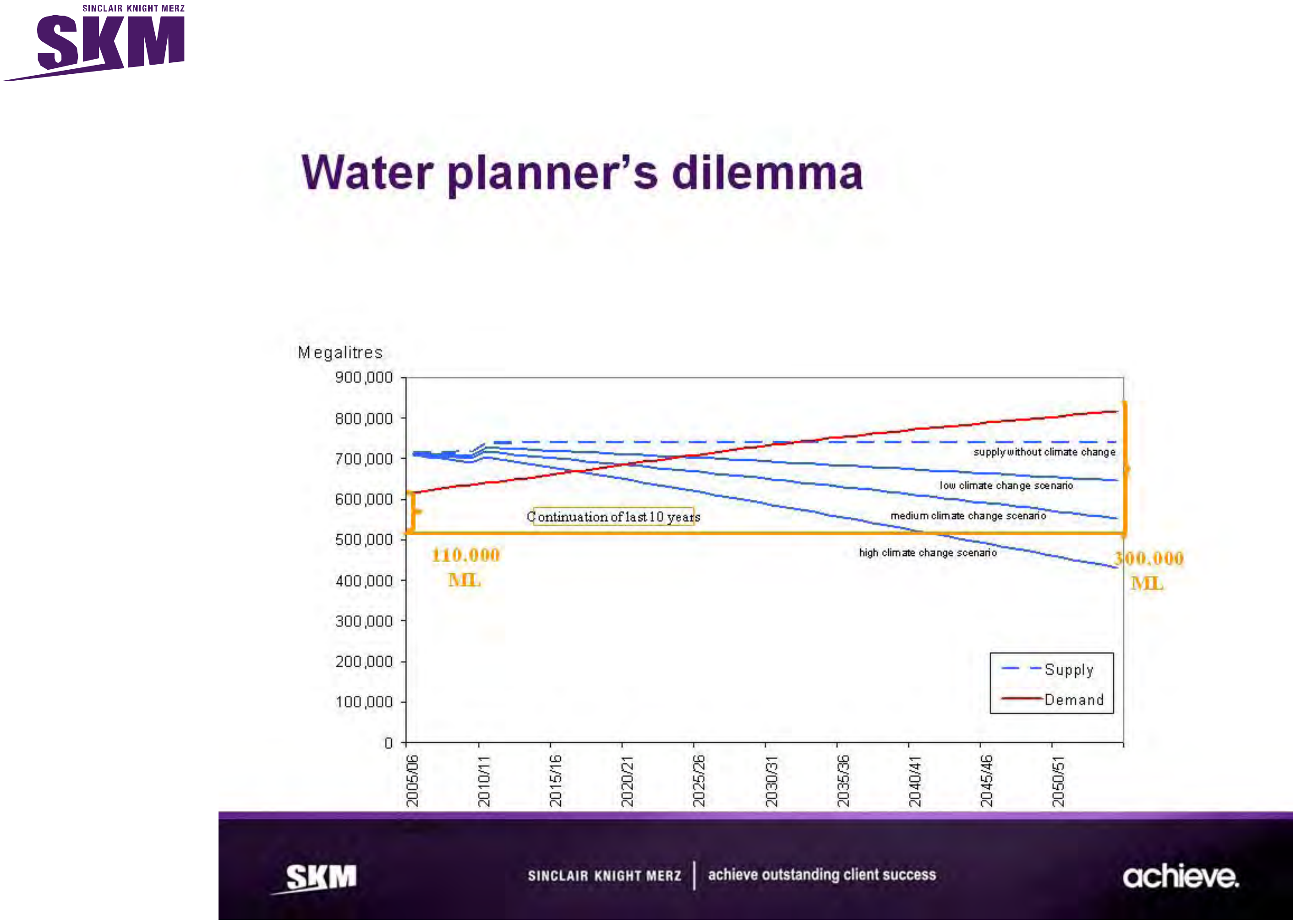
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Water planner's dilemma
Megalitres
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
2005/06
2010/11
2015/16
2020/21
2025/26
2030/31
2035/36
2040/41
2045/46
2050/51
supply without climate change
low climate change scenario
medium climate change scenario
high climate change scenario
Continuation of last 10 years
110,000
ML
300,000
ML
Supply
Demand
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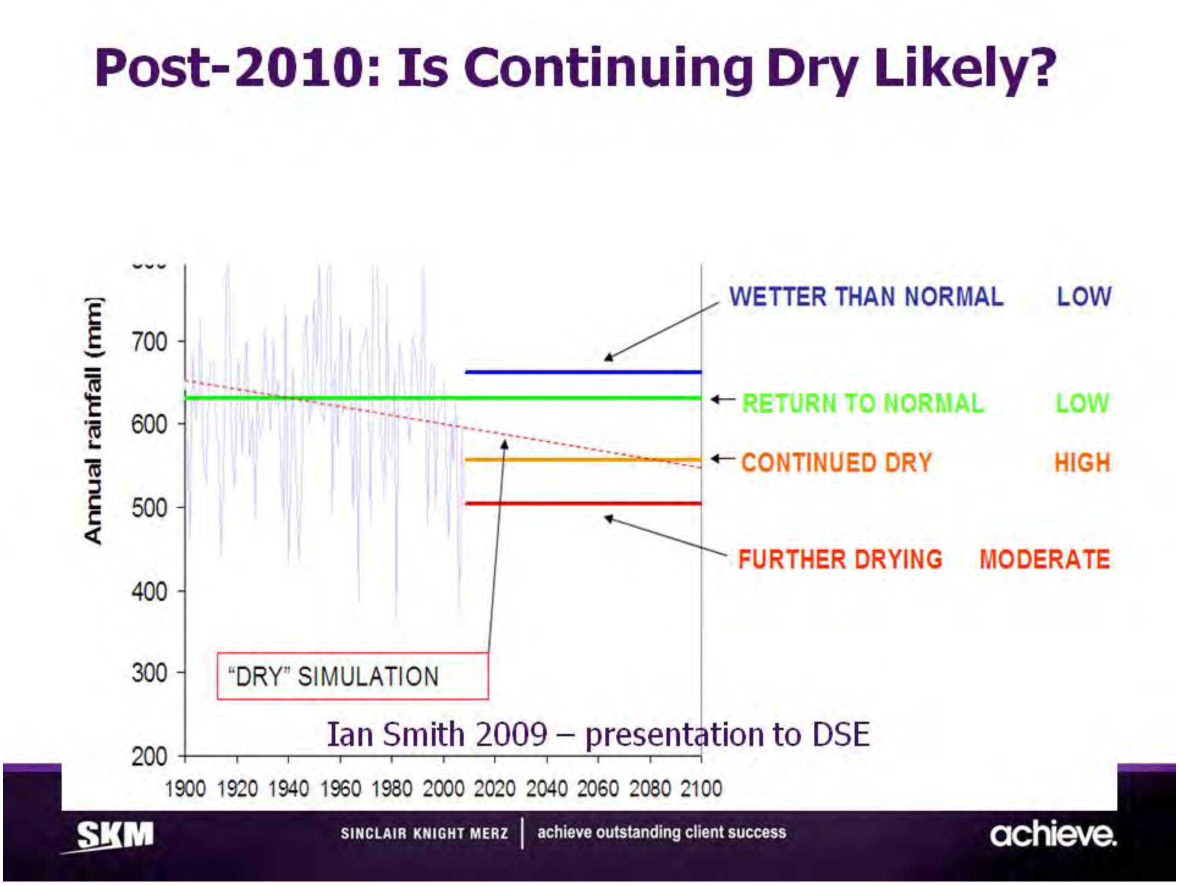
Post-2010: Is Continuing Dry Likely?
Annual rainfall (mm)
700
600
500
400
300
200
1900 1920 1940 1960 1980 2000 2020 2040 2060 2080 2100
WETTER THAN NORMAL LOW
RETURN TO NORMAL LOW
CONTINUED DRY HIGH
FURTHER DRYING MODERATE
"DRY" SIMULATION
Ian Smith 2009 – presentation to DSE
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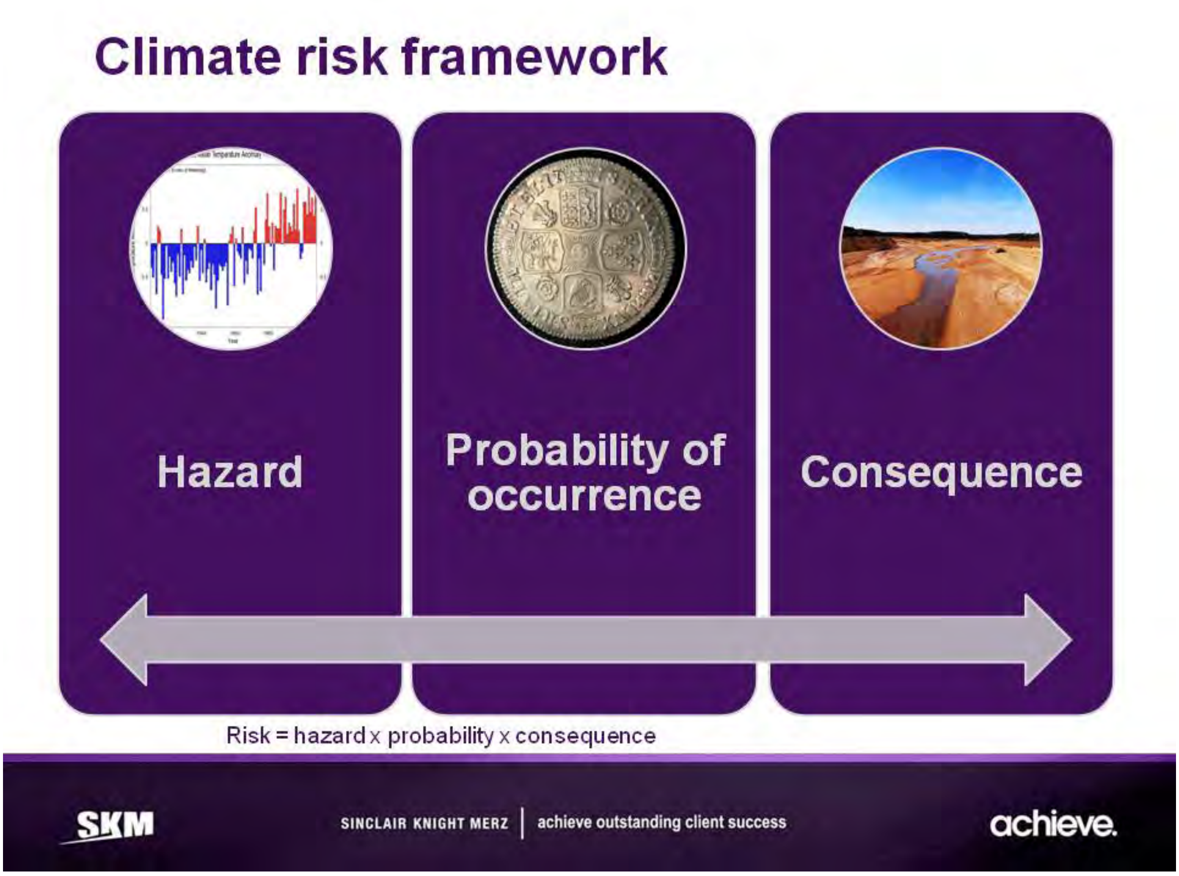
Climate risk framework
Hazard
Probability of occurrence
Consequence
Risk = hazard x probability x consequence
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Climate risk framework

Hazard	Probability	WQ consequence	Salinity consequence	Ecosystem consequence	People consequence
CO2 fertilisation	High	M	L	H	L
Rain - seasonal changes	High	M	L	H	M
Drought intensity increase	High	H	H	H	H
Higher potential ET	Medium	L	L	M	M
Groundwater recharge change	High	M	H	H	H
Bushfire intensity increase	High	H	L	H	H

Hazard and probability can be changed to reflect 'upper' & 'lower' bounds

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MDBA climate history to date

- SEACI Phase 1: 2006-2009 (CSIRO/BOM)
- Risks program 2006-2010
- Phase 1 Climate Syntheses and preliminary policy analysis completed June 2009 (SKM)
- 9 Climate science reviews completed Aug 2009
- SEACI Phase 2 commences July 2009 (CSIRO/BOM)
- MDBA/NCCARF Climate science workshop March 2010
- 4 climate risk projects
- Remaining gaps funded 2010/11

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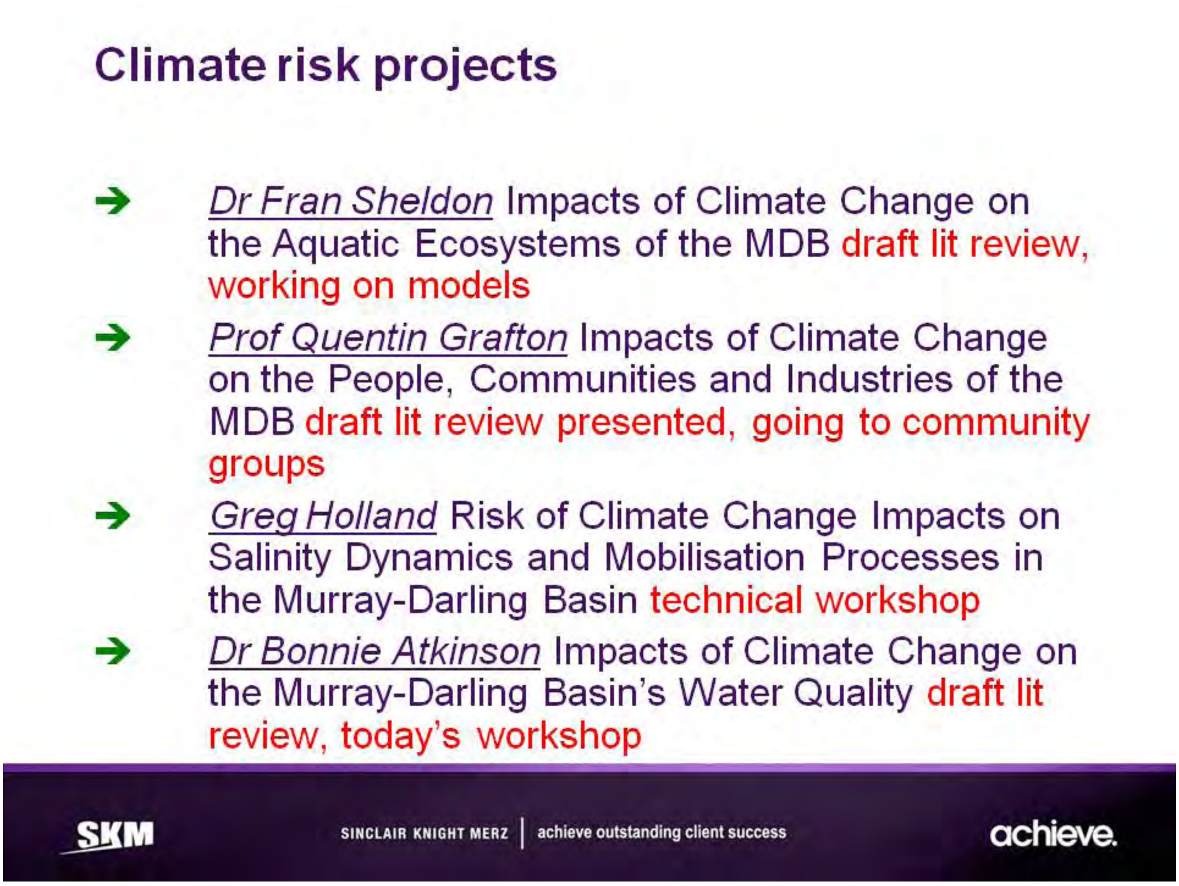
Climate risk projects
Dr Fran Sheldon Impacts of Climate Change on the Aquatic Ecosystems of the MDB draft lit review, working on models
Prof Quentin Grafton Impacts of Climate Change on the People, Communities and Industries of the MDB draft lit review presented, going to community groups
Greg Holland Risk of Climate Change Impacts on Salinity Dynamics and Mobilisation Processes in the Murray-Darling Basin technical workshop
Dr Bonnie Atkinson Impacts of Climate Change on the Murray-Darling Basin's Water Quality draft lit review, today's workshop
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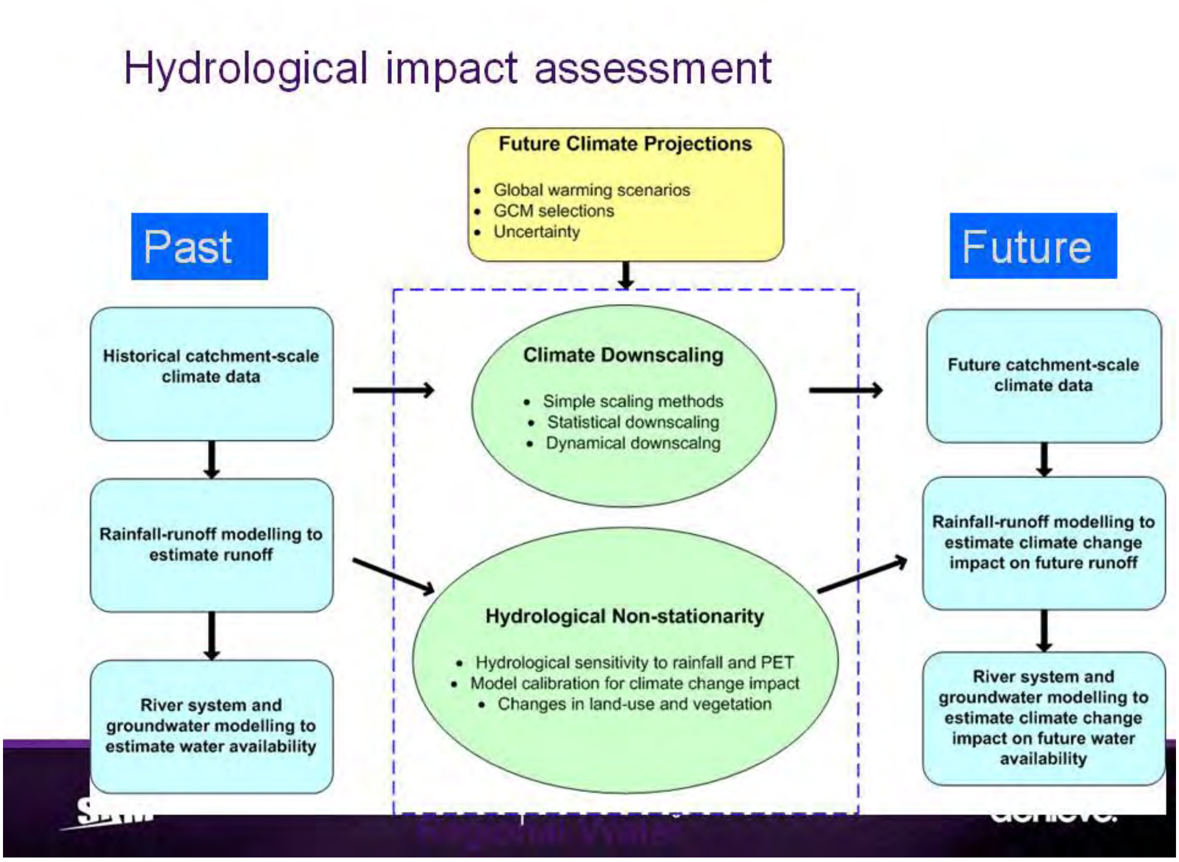
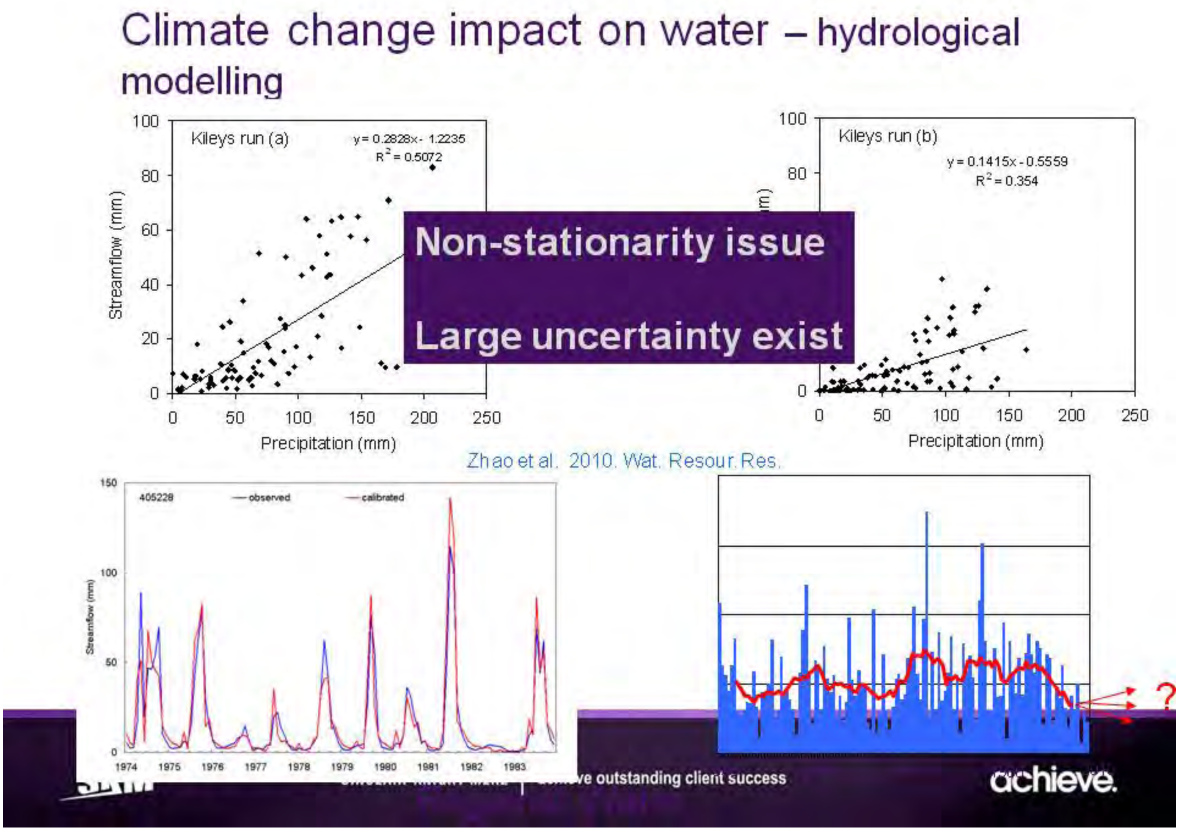

Hydrological impact assessment
Future Climate Projections
Global warming scenarios
GCM selections
Uncertainty
Past
Future
Historical catchment-scale climate data
Climate Downscaling
Simple scaling methods
Statistical downscaling
Dynamical downscalng
Future catchment-scale climate data
Rainfall-runoff modelling to estimate runoff
Rainfall-runoff modelling to estimate climate change impact on future runoff
Hydrological Non-stationarity
Hydrological sensitivity to rainfall and PET
Model calibration for climate change impact
Changes in land-use and vegetation
River system and groundwater modelling to estimate water availability
River system and groundwater modelling to estimate climate change impact on future water availability


Climate change impact on water – hydrological modelling
Kileys run (a)
y = 0.2828x - 1.2235
R^2 = 0.5072
Streamflow (mm)
Precipitation (mm)
Kileys run (b)
y = 0.1415x - 0.5559
R^2 = 0.354
Non-stationarity issue
Large uncertainty exist
Zhao et al. 2010. Wat. Resour. Res.
405228
observed
calibrated
Streamflow (mm)
?
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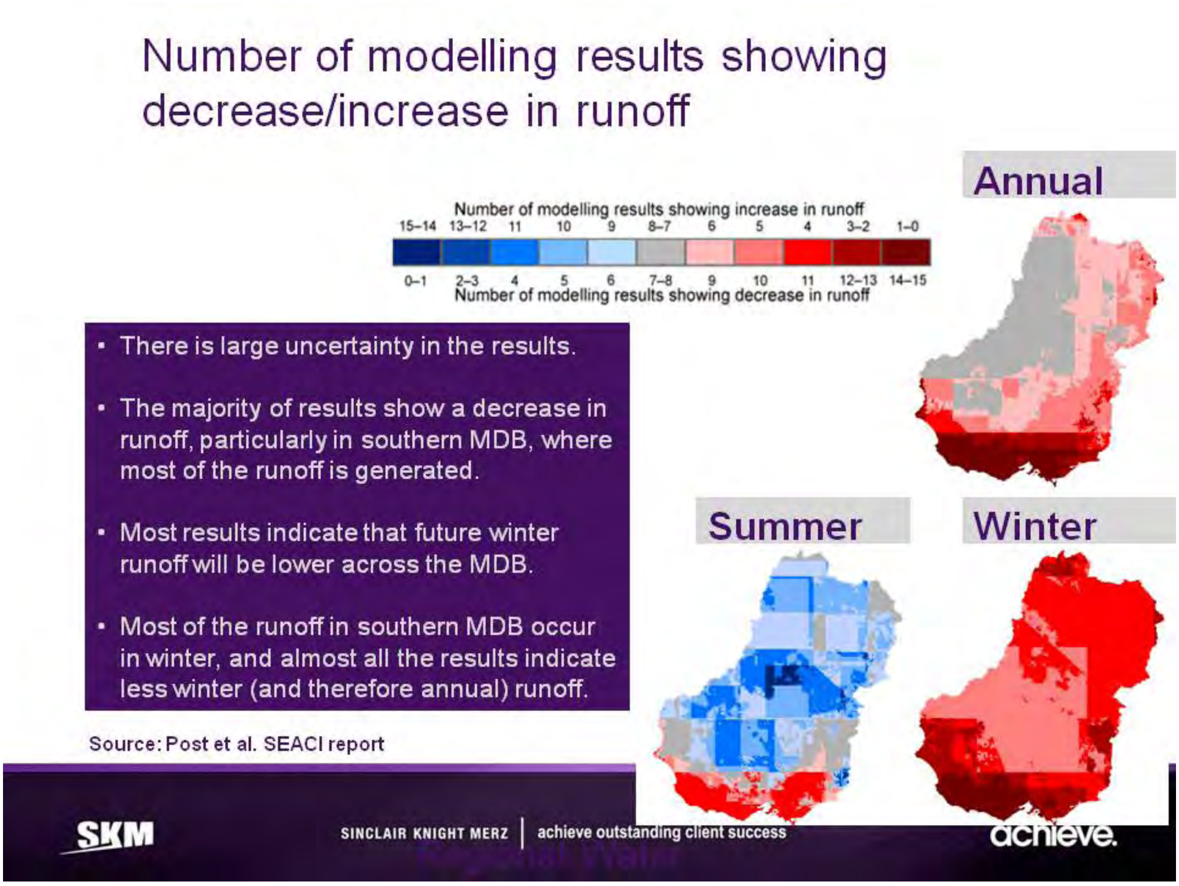

Number of modelling results showing decrease/increase in runoff
Annual
Number of modelling results showing increase in runoff
15–14 13–12 11 10 9 8–7 6 5 4 3–2 1–0
0–1 2–3 4 5 6 7–8 9 10 11 12–13 14–15
Number of modelling results showing decrease in runoff
▪ There is large uncertainty in the results.
▪ The majority of results show a decrease in runoff, particularly in southern MDB, where most of the runoff is generated.
▪ Most results indicate that future winter runoff will be lower across the MDB.
▪ Most of the runoff in southern MDB occur in winter, and almost all the results indicate less winter (and therefore annual) runoff.
Summer
Winter
Source: Post et al. SEACI report
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ALTERNATIVE APPROACHES

1. Use MDBSYP scenarios (3 or 5)
2. Make use of the historical climate change record
3. Use best available knowledge of climate change features in a climate risk framework
4. Use a combination of approaches

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Appendix E Climate scenarios for MDBA climate risks projects – discussion paper

1. Requirements of the brief

Extract from brief:

'**Climate change has been identified as having probably the greatest future impact on water availability in the Basin**. While the broad impacts of climate (eg seasonal variations in rainfall and temperature) on the Basin are expected to be addressed in phase 2 of the South Eastern Australian Climate Initiative (coordinated by the MDBA), it will not include the direct and indirect impacts of climate change on water quantity and quality per se.

A number of real and potential risks to the quantity and quality of the Basin's water resources have been identified. The risks are complex and their impacts vary across the Basin. **The interactions between risks, their cumulative impacts and effectiveness of current actions need to be better understood.** Strategies for addressing or managing such risks will need to be developed, while new and emerging risks are also identified and assessed.

The Risk Assessment Program within MDBA's NRM Division is seeking to initiate the investigation of a range of such risks. These can be broadly clustered into: **risks driven by climate change (eg drought, bushfire, salinity dynamics)**; risks relating to catchment processes (eg forest hydrology, afforestation, invasive species, floodplain dynamics, land use); and risks arising from direct water interception and use (eg farm dams, stock and domestic, current management arrangements).

The findings and knowledge gained from these projects will be synthesised into a coherent framework to serve as a basis for the management of risks to the Basin's water resources for the long term. **Risk assessments made through a sound framework** will inform the development of better management strategies by anticipating the impacts of these risks, the likelihood of their occurrence and their consequences."

The brief specifies that the group of climate-related projects are to use the same range of three climate scenarios in their study, namely:

I. A 'most favourable 2030 scenario' that is based on a continuation of the long-term (1895 to 2006) averages for rainfall and runoff across the MDB

II. A ‘medium 2030 scenario’ that is based upon the medium global warming scenario and associated rainfall and runoff described in the CSIRO report “Water Availability in the Murray Darling Basin” of October 2008, and

III. A ‘least favourable 2030 scenario’ that is based upon the actual climate of the MDB in the period 1997–2006 (this includes 15% less rainfall and 50% less runoff in the southern MDB when compared with the long-term average).

No-one has questioned the use of the proposed scenarios in the project brief. However the specification of the climate scenarios is an important step (maybe the most important step?) in assessing potential impacts, given the aim of these projects is to assess potential climate change impacts.

The key issues around the climate scenarios and their use in the projects include:

1. What do **policy makers and water planners/managers** need to know about future CC impacts? Essentially they need to plan for the full range of potential CC impacts. However there is considerable uncertainty about what the ‘full range’ is, the current level of CC impacts, and the timing of future impacts.
2. CSIRO/BOM has developed CC scenarios based on GCM simulations. These scenarios account for the differences between GCM results (model uncertainty) and differences between GHG emission scenarios (emissions uncertainty). The CSIRO developed a slightly different set of climate scenarios to 2030 for use in the MDBSYP (including 15 rather than 23 GCMs).
3. The CSIRO MDBSYP CC scenarios do not take into account the main drivers of **climate variability** in the MDB (e.g. ENSO, ENSO-Modoki, SAM, STR, IOD). Hence the current drought (the Big Dry: 1996-2009), which is considerably more severe than the 2030 CSIRO CC forecasts, is not incorporated in the CSIRO scenarios. Given the evidence (SEACI phase 1) that there may be a link between CC and the regional climate modes (e.g. strong correlation between global warming and intensity of STR), it could be argued that the CSIRO climate scenarios (a) do not provide for a sufficiently wide range of potential CC impacts and (b) may have a timing issue if indeed CC impacts are already somewhat stronger than GCMs suggest.
4. The climate scenarios presented in the project brief are not 3 climate change scenarios. Two are different **historic baselines** and one is a median climate scenario (of 45 variants). This may mean that ‘climate change’ is not adequately tested as only a median is represented. One alternative is to adopt the MDBSYP approach by including 3 CC scenarios plus 2 baseline scenarios. Planners however may be interested in a **‘worst case’ scenario**, which could be derived from (a) examining the palaeo record (e.g. the ‘50-year drought’) or (b) applying CC scenarios to the Big Dry (1996-2009) baseline. However the flow implications have not been assessed and so such ‘worst case’ scenarios can only be considered qualitatively.

5. There may be an issue that the ‘historical instrumental record’ already incorporates a significant amount of CC impact, particularly since the 1950s. This may be a confounding factor in ‘baseline’ scenarios. On the other hand, CC observations may be considerably more reliable than future projections. Hence analysis of CC impacts in the observational record could be included.
6. The project proposals generally do not examine all the well known **features of climate change**. There is a primary focus on rainfall-induced changes to water quantity/availability. However other direct physical impacts (e.g. temperature change, ET change, CO2 fertilisation, droughts, floods, heatwaves, storms/cyclones) and indirect physical impacts (e.g. bushfires, soil moisture, groundwater recharge, vegetation responses, land use change, other interception risks) and non-physical indirect impacts (e.g. ETS, voluntary offsets, Basin Plan, consumer preferences, new technologies) are partially or not addressed.
7. The **baseline** against which CC impacts are to be measured is only considered in the aquatic ecosystems proposal. In this proposal there is a request to provide modelled ‘natural’ pre-development flow data to assist assessments of change. The use of the ‘historical instrumental climate record’ could be considered as a baseline, but it does incorporate climate change since 1950. **What is the baseline or reference condition is a fundamental question**.
8. How will the projects differentiate between CC and normal CV (i.e. CV without a CC forcing)? What can be learnt from CV, especially the **Big Dry**, about future CC scenarios?

   Recommendation: A separate discussion paper on the selection of climate scenarios is probably necessary. Need to ensure a sufficiently wide range is covered and common key features addressed in projects. This should be discussed at the first combined workshop. A climate scientist should attend.

2. MDSYP Climate-Water Scenarios

Extract from: *Chiew FHS, Teng J, Kirono D, Frost AJ, Bathols JM, Vaze J, Viney NR, Young WJ, Hennessy KJ and Cai WJ (2008) Climate data for hydrologic scenario modelling across the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 35pp.* (Prof Roger Grayson provided technical review of the report).

Scenarios

This report describes the climate data for the three climate scenarios used for the hydrological modelling in the project. The three climate scenarios are (1) historical climate, (2) recent climate, and (3) future climate.

All three climate scenarios have 112 years of daily climate data for 0.05o x 0.05o (5 km x 5 km) grid cells across the Murray-Darling Basin (MDB).

The historical climate scenario (Scenario A) is the baseline against which other scenarios are compared. It is based on observed SILO Data Drill climate data from 1895 to 2006.

The recent climate scenario (Scenario B) is used to assess future water availability should the climate in the future prove to be similar to that of the last ten years. Climate data for 1997 to 2006 are used to generate stochastic replicates of 112-year daily climate sequences. The replicate which produces a mean annual runoff closest to that observed in 1997 to 2006 is selected to define this scenario.

The future climate scenario (Scenario C) is used to assess the range of likely climate conditions around the year 2030. Forty-five future climate variants, each with 112 years of daily climate sequences, are used. The future climate variants come from scaling the 1895 to 2006 climate data to represent ~2030 climate, based on analyses of 15 global climate models (GCMs) and three global warming scenarios from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4).

GCM predictions

There is considerable uncertainty in the global warming projections and in the predictions of how global warming affects local rainfall. There are very significant differences in the future rainfall projections between the 15 GCMs. However, the majority of the GCMs shows a decrease in future mean annual rainfall**. The best estimate or median indicates that the future mean annual rainfall in the MDB in ~2030 relative to ~1990 will be lower by about 2 percent in the north to 5 percent in the south.** Averaged across the MDB, the best estimate or median is a 2.8 percent decrease in mean annual rainfall. The extreme dry and extreme wet estimates in the northern half of the MDB range from a 10 to 15 percent decrease to a 10 to 15 percent increase in mean annual rainfall. In the southern half of the MDB, the extreme estimates range from a 15 to 20 percent decrease in mean annual rainfall to a 5 to 10 percent increase in mean annual rainfall, and **in the southernmost parts, the extreme estimates range from a decrease in mean annual rainfall of about 20 percent to little change in mean annual rainfall.** Averaged across the MDB, the extreme estimates range from a 13 percent decrease to an 8 percent increase in mean annual rainfall. **Most of the GCMs indicate that future winter rainfall is likely to be lower across the MDB.** Most of the rainfall and runoff in the southern MDB occur in the winter half of the year, and almost all the GCMs indicate lower future winter rainfall there.

Accuracy of historical instrumental data

Rainfall: Rainfall is much more variable, both temporally and spatially, compared to the other climate variables. There is good coverage of rainfall stations in the south and east of the MDB where most of the runoff comes from, and sparser coverage in the north-west where there is little runoff. The relative paucity of rainfall stations in the less populated, mountainous and extreme high rainfall areas in the far south-east is of some concern because this area generates substantial runoff and is characterised by large spatial rainfall gradients.

The source of the data is the SILO Data Drill of the Queensland Department of Natural Resources and Water (http://www.nrw.qld.gov.au/silo and Jeffrey et al., 2001). The SILO Data Drill provides surfaces of daily rainfall and other climate data interpolated from point measurements made by the Australian Bureau of Meteorology. The gridded climate data is derived from observations that have been quality checked by the Australian Bureau of Meteorology and have been subject to error checking by the Queensland Department of Natural Resources and Water. Nevertheless, it is inevitable that there will still be errors in the data and the interpolation routines can also introduce errors.

Evaporation: The daily areal potential evapotranspiration (APET) is calculated from 0.05o x 0.05o climate data from the SILO Data Drill (temperature; relative humidity, calculated as actual vapour pressure divided by saturation vapour pressure; and incoming solar radiation) using Morton's wet environment evapotranspiration algorithms (http://www.bom.gov.au/averages and Morton, 1983; Chiew and Leahy, 2003). The APET is defined as the evapotranspiration that would take place, if there was unlimited water supply, from an area large enough that the effects of any upwind boundary transitions are negligible, and local variations are integrated to an areal average. The APET is therefore conceptually the upper limit to actual evapotranspiration in the rainfall-runoff modelling. (Note: APET is not a measured variable – rather values are derived based on theoterical assumptions.)

Runoff:

Rainfall-runoff simulation: Daily rainfall and potential evapotranspiration (PET) are required as input data for the rainfall-runoff modelling. The rainfall-runoff modelling results are much less sensitive to errors in the PET data than they are to errors in the rainfall data. It is also easier to provide reliable PET data for the rainfall-runoff modelling, because compared to rainfall, PET is relatively conservative in space with little day-to-day variation.

Future climate scenarios (2006-2030)

The future climate series (Scenario C) is obtained by scaling the historical daily climate series from 1895 to 2006 (Scenario A). Hence the daily climate series for Scenarios A and C have the same length of data (112 years) and the same sequence of daily climate (nb potential changes in the frequency and timing of daily rainfall are not considered). **Scenario C is therefore not a forecast climate at 2030**, but a 112-year daily climate series based on 1895 to 2006 data for projected global temperatures at ~2030 relative to ~1990.

To provide a basis for estimating future climate change, the IPCC (2000) Special Report on Emission Scenarios (SRES) prepared 40 greenhouse gas and sulphate aerosol emission scenarios for the 21st century that combine a variety of assumptions about demographic, economic and technological factors likely to influence future emissions. Each scenario represents a variation within one of four 'storylines' (A1, A2, B1 and B2, see Table 4-1) with projected carbon dioxide, methane, nitrous oxide and sulphate aerosol emissions associated with each of the scenarios.

The IPCC has not provided temperature projections for 2030 for Australia. These were derived by CSIRO and Australian Bureau of Meteorology (2007). **The three predictions of the temperature change by ~2030 relative to ~1990 are: a low global warming of 0.45C (low end of SRES B1), medium global warming of 1.03C (average of the low and high global warming scenarios), and high global warming of 1.60C (high end of SRES A1T). (Note the observed increase 1990-2010 is 0.2C).**

To account for the uncertainty in GCM simulation of future climate across the MDB, archived results from 15 of the 23 IPCC AR4 GCMs are used in this project. The GCM data are obtained from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) website (http://www-pcmdi.llnl.gov). This project uses data from only 15 of the 23 GCMs because Scenario C future climate series were required to run the hydrological models in June 2007, and at that time only 15 GCMs were analysed and readily available. These 15 GCMs also have readily available daily rainfall data.

For each GCM, and for each season and each GCM grid point, the simulated rainfall (or other climate variable) is plotted against simulated global average temperature. A linear regression is fitted through the data points and the slope of the linear regression gives the change in rainfall (or other climate variable) per degree of global warming (see Figure 4-2).

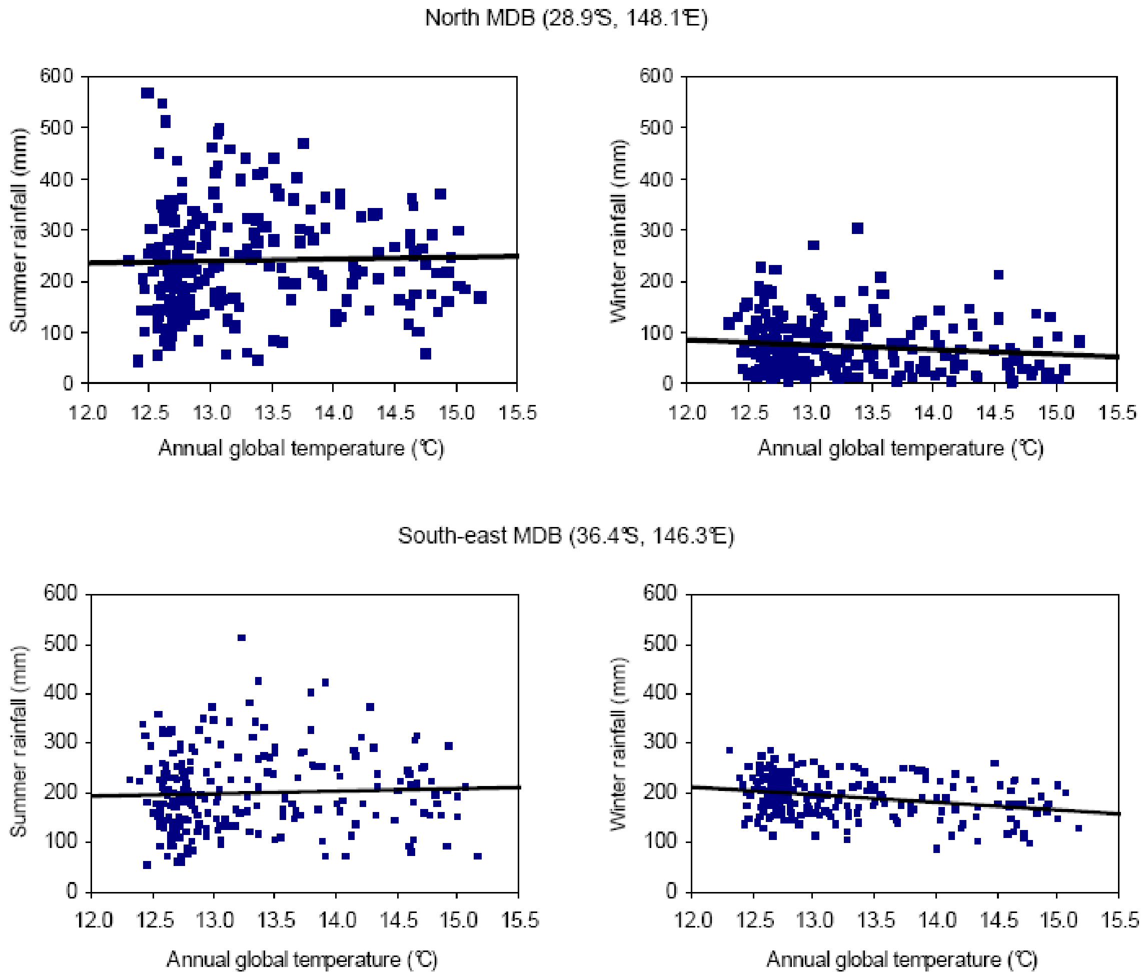


Figure 4-2. Example plots showing method used to estimate change in rainfall per degree global warming
(Plots show summer (DJF) and winter (JJA) rainfall versus global average temperature from CSIRO-MK3.0 GCM simulations for 1895 to 2100 for two selected GCM grids in the MDB, with the slope of the regression line giving the rainfall change per degree global warming)

The absolute change in the climate variable per degree of global warming is converted to a percent change per degree global warming relative to the model baseline climate of 1975 to 2005 (except in the case of temperature where the absolute value is used). In particular, the percent change is used for rainfall to reduce the effect of errors in the baseline climate on the magnitude of the simulated change (Whetton et al., 2005). Combinations of results from many runs for the same GCM are used (generally all A1B simulations for rainfall and temperature, and a combination of A1B and A2 runs for the other climate variables) to estimate the change in the climate variable per degree global warming. Relative humidity and incoming solar radiation data are not available for seven GCMs and are instead obtained from another GCM which matches the change in temperature most closely for each of these seven GCMs. The percent changes in the climate variables per degree global warming for each of the four seasons for the 15 GCMs are multiplied by the change in temperature for each of the three global warming scenarios to obtain the 45 sets of 'seasonal scaling' factors. The seasonal scaling factors are then used to scale the historical daily climate data from 1895 to 2006 to obtain the 45 future climate variants, each with 112 years of daily climate data. (Presumably for each reporting region).

Rainfall is the main driver of runoff, with a 1 percent change in mean annual rainfall generally amplified to a 2 to 3.5 percent change in mean annual runoff. A 1 percent increase in mean annual APET generally leads to a 0.5 to 0.8 percent decrease in mean annual runoff (Chiew, 2006b; Jones et al., 2006). These are very general rules of thumb, and the daily future climate series obtained here are used in the rainfall-runoff modelling to provide more accurate results (see Chiew et al., 2008).

There is much better agreement in the future temperature projections from the 15 GCMs compared to the rainfall projections. The projections for the medium global warming scenario generally show a temperature increase of 0.6 to 1.5 $_o$C, with the northern MDB showing greater warming. The GCMs indicate that the change in relative humidity by ~2030 relative to ~1990 is generally less than 3 percent and that the change in incoming solar radiation is generally less than 1 percent. The temperature, relative humidity and incoming solar radiation are not used directly for the rainfall-runoff modelling, but are used to calculate the APET series required to run the rainfall-runoff model.

3 emission scenarios (high, medium, low) + 15 GCM runs for each emission scenario = 45 variants. The 3 future scenarios are taken as median, 2nd highest rainfall across MDB, 2nd lowest rainfall.

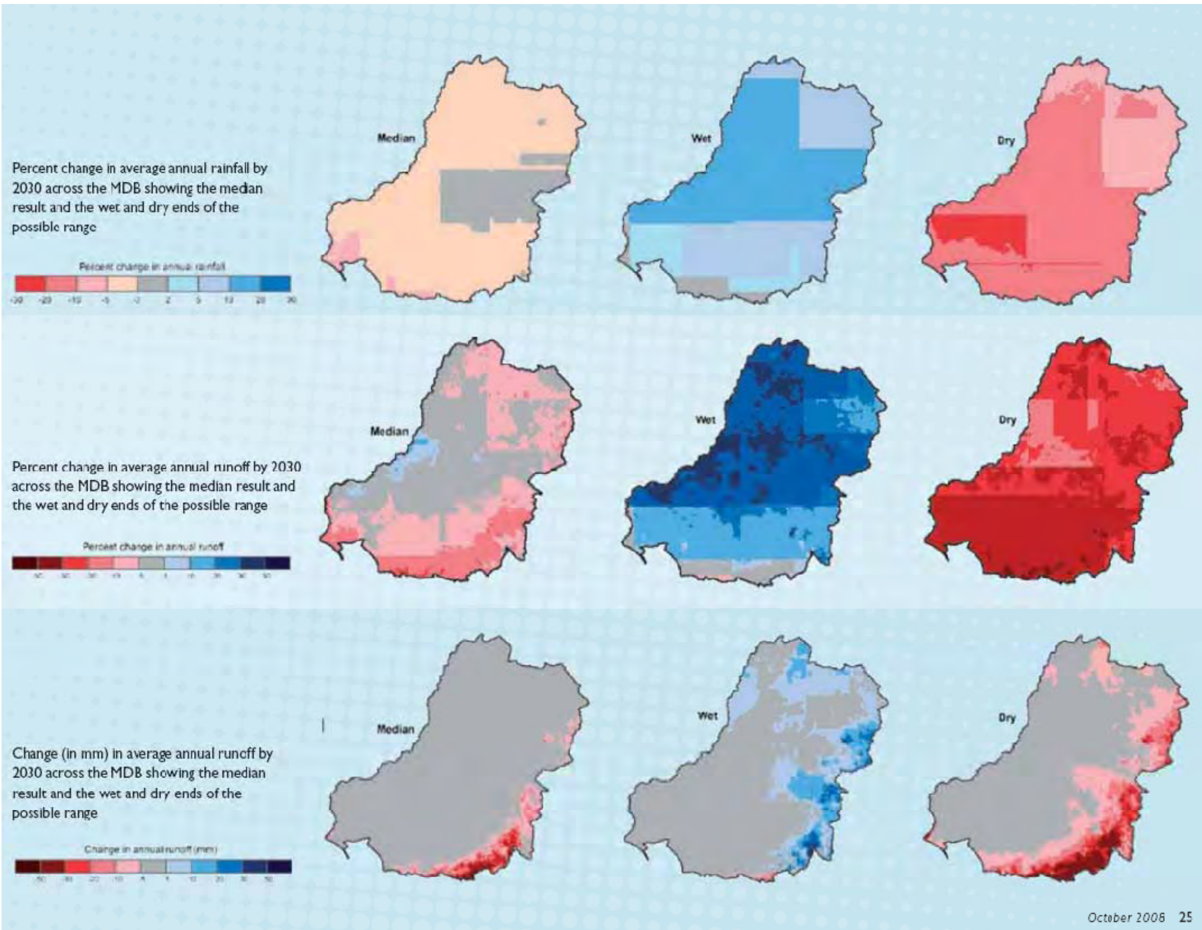
The median 2030 climate from the 45 scenarios indicates reductions in average annual rainfall of about 2 percent in the north of the MDB and about 5 percent in the south of the MDB. Averaged across the entire MDB the median 2030 climate indicates a 3 percent reduction in average annual rainfall. These changes in rainfall translate to reductions in average annual runoff of 5 to 10 percent in the north-east and southern MDB and 15 percent in the southernmost areas. Averaged across the entire MDB, there would be a 9 percent reduction in average annual runoff.

The possible range (from the second wettest to the second driest of the 45 climate scenarios) in average annual runoff outcomes for the northern half of the MDB is from a reduction of up to 30 percent to an increase of up to 30 percent. For the southern half of the MDB, the possible range in average annual runoff outcomes is from a reduction of up to 40 percent to an increase of up to 20 percent. **In the southernmost areas of the MDB, the possible range in average annual runoff outcomes for the southernmost areas of the MDB is from a reduction of up to 50 percent to very little change in average annual runoff.**

The possible range in average annual runoff outcomes averaged over the entire MDB is from a reduction of up to 33 percent to an increase of up to 16 percent.

The adjacent maps show the full spatial pattern of the percent change in the median rainfall and runoff and the extremes of the possible range. The patterns on the rainfall and runoff change maps are largely due to ranking of the rainfall and runoff results from the 45 climate scenarios for every 5 km by 5 km grid cell. The patterns also reflect the large and differing grid cells of GCMs. The patterns on the runoff change maps differ from those on the rainfall change maps because of the non-linear nature of the transformation of rainfall into runoff.

The full spatial pattern of the absolute changes (in mm) in the median average annual runoff and the extreme of the possible range are also shown on the maps. These maps clearly indicate the runoff changes that will largely determine changes in streamflow will occur in the high runoff areas of the south and east of the MDB.



The total current surface water resource of the MDB can be considered in several ways:

- the sum of the surface runoff generated across the MDB land surface (28,900 GL/year)
- the sum of water availability across all 18 regions, including the internally generated portion of surface water availability for the Barwon-Darling and Murray regions (23,417 GL/year)
- the water availability for the MDB, assessed at Wentworth (14,493 GL/year)
- streamflow at the mouth of the Murray River (12,233 GL/year).

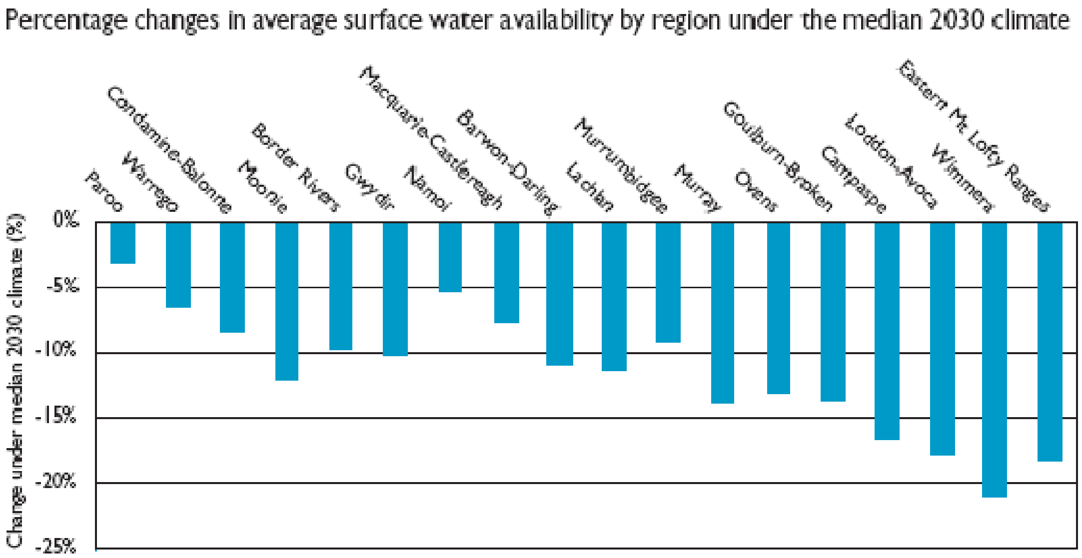
These different assessments of water availability include different proportions of the natural water losses in the MDB and are based on modelling without consumptive water use. The last three of the above assessment options also include the inter-basin transfer contributions to streamflow in the MDB from the Snowy Mountain Hydro-electric Scheme. The net 1010 GL/year transfer is equivalent to about 3 percent of the 28,900 GL/year of runoff generated across the MDB.

The 23,417 GL/year sum of water availability is suggested to be the most useful assessment of the total current surface water availability for the MDB as it:

- is assessed at the points of maximum available flow in each of the regions – points where the surface water models are well calibrated
- includes some but not all of the natural losses which occur as water moves through the MDB, thus providing a reliable integrative measure of the total accessible surface water resource.

The impact of the median 2030 climate on average surface water availability across the MDB would be 11 percent reduction, or 2481 GL/year less surface water on average. Integrating down through the connected river system of the MDB, and thus incorporating the natural water losses, the reduction at Wentworth on the Murray River would be 1682 GL/year less surface water on average (or a 12 percent reduction).

This proportional reduction in water availability due to climate change varies considerably between regions from a 3 percent reduction in the Paroo to a 21 percent reduction in the Wimmera. Much of the reduction in surface water availability would occur in the south-east of the MDB, where firstly, most of the runoff in the MDB is generated, and secondly, the impact of climate change is likely to be greatest. Thus, 67 percent of the water availability reduction across the 18 regions is a result of the reductions in the Goulburn-Broken, Ovens, Murray and Murrumbidgee regions (including the reductions in the contribution from the Snowy Mountains Hydro-electric Scheme).



There is a large uncertainty associated with climate change impacts by 2030. Summed across regions the change in surface water availability ranges from an 11 percent increase (2631 GL/year) under the wet extreme 2030 climate to a 34 percent reduction (7893 GL/year) under the dry extreme 2030 climate. In terms of the streamflow changes integrated down through the connected river system of the MDB to Wentworth, the climate change impacts range from a 7 percent increase under the wet extreme 2030 climate to a 37 percent reduction under the dry extreme 2030 climate with a median reduction of 12 percent.

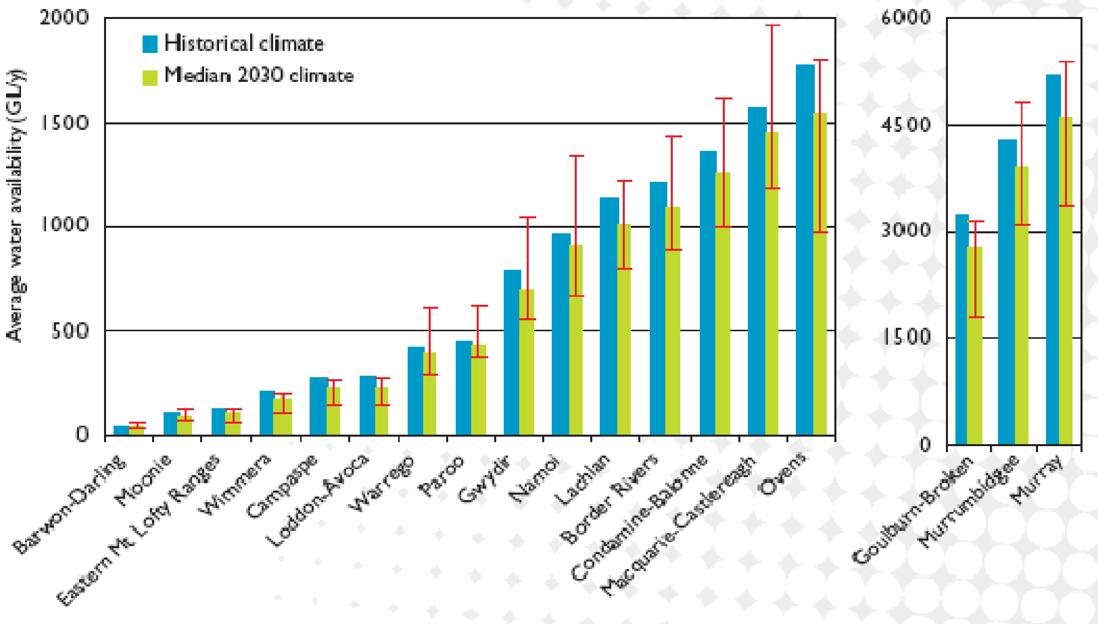
Effect of climate change by 2030 on water availability (GL/year) for each region and the MDB

	Historical climate	2030 climate		
		Wet extreme	Median	Dry extreme
	GL/y			
Paroo	445	626	432	372
Warrego	420	619	393	292
Condamine-Balonne	1,363	1,616	1,249	1,004
Moonie	98	122	87	70
Border Rivers	1,208	1,427	1,092	891
Gwydir	782	1,049	703	554
Namoi	965	1,336	915	677
Macquarie-Castlereagh	1,567	1,967	1,450	1,180
Barwon-Darling*	41	61	40	32
Lachlan	1,139	1,212	1,012	792
Murrumbidgee	4,270	4,816	3,881	3,087
Murray*	5,211	5,391	4,614	3,358
Ovens	1,776	1,802	1,542	974
Goulburn-Broken	3,233	3,146	2,792	1,788
Campaspe	275	263	230	148
Loddon-Avoca	285	270	234	146
Wimmera	219	207	173	102
Eastern Mount Lofty Ranges	120	117	99	58
Total	**23,417**	**26,047**	**20,936**	**15,524**
MDB integrated to Wentworth	14,493	15,450	12,811	9,155

*For the Barwon-Darling and Murray regions only the fraction of the water availability generated within the region is shown

SINCLAIR KNIGHT MERZ SKM

Average surface water availability (GL/year) for each region in the MDB under the historical and median 2030 climates; the uncertainty range for future climate is indicated. For the Barwon-Darling and Murray regions only the fraction of the water availability generated within the region is included



LIMITATIONS TO THE CSIRO SCENARIOS

CSIRO would be the first to recognise limitations in the MDBSYP climate-water scenarios. Some of the limitations are:

a. Hydrological simulations rely on climate inputs. Hence the model outputs are only as good as the climate inputs.
b. The hydrological modelling relies on outputs of 15 GCM models. However the GCM models give widely differing projections, particularly for rainfall in the MDB. This is because the GCMs are constructed differently, emphasise processes differently, and vary in the number of processes included.
c. The GCMs currently have poor resolution at the MDB spatial scale.
d. The GCMs do not include the principal climate modes that affect the climate of the MDB (ENSO, ENSO-Modoki, STR, SAM, IOD and Blocking Highs).
e. The GCMs do not include surface-atmosphere feedbacks.
f. The GCMs use SRES emission scenarios. Current emissions are higher than the SRES (2000) worst case.

g. The hydrologic models simply scale the historic record to determine future outcomes at 2030. They do not model climate change per se.
h. The MDSYP took the baseline period as 1895-2006. This period includes the effects of post-industrial climate change (approx 0.8C temperature increase globally), so is not a ‘no climate change’ baseline. Future scenarios thus attempt to assess ‘additional climate change’ to 2030 (from a 1990 baseline).
i. The 1895-2006 baseline does not account for the full range of natural climate variability (ie without CC). Palaeo-evidence for example shows severe droughts lasting up to 50 years.
j. The 1895-2006 baseline includes a significant amount of land use change that itself affects the climate.

In favour of the CSIRO MDBSYP climate-water scenarios is that they are the only set available which provide daily streamflow data as outputs for all catchments across the MDB at 2030. But the question remains, – what does using these scenarios really mean given their limitations? And what are the alternative approaches?

How do the GCMs perform?

In their favour

The GCMs agree on the direction of temperature warming (although the range in predictions is high).

The GCMs show on average greater drying in the southern part of the Basin. This is a strong feature of the current drought (1996-2009) that was not prevalent in previous droughts in the instrumental record.

Equivocal

The GCMs agree on a predominant winter rainfall decline. However the predominant decline to date is autumn, with winter second.

The GCMs on average predict an increase in PET by 2030. However there is some confusion as to whether potential evaporation and actual evaporation are increasing or decreasing.

Against

The GCMs vary widely in rainfall amount prediction. This seems little more than guesswork?

Alternative Approaches

1. **Use the CSIRO MDBSYP climate scenarios (all five)**

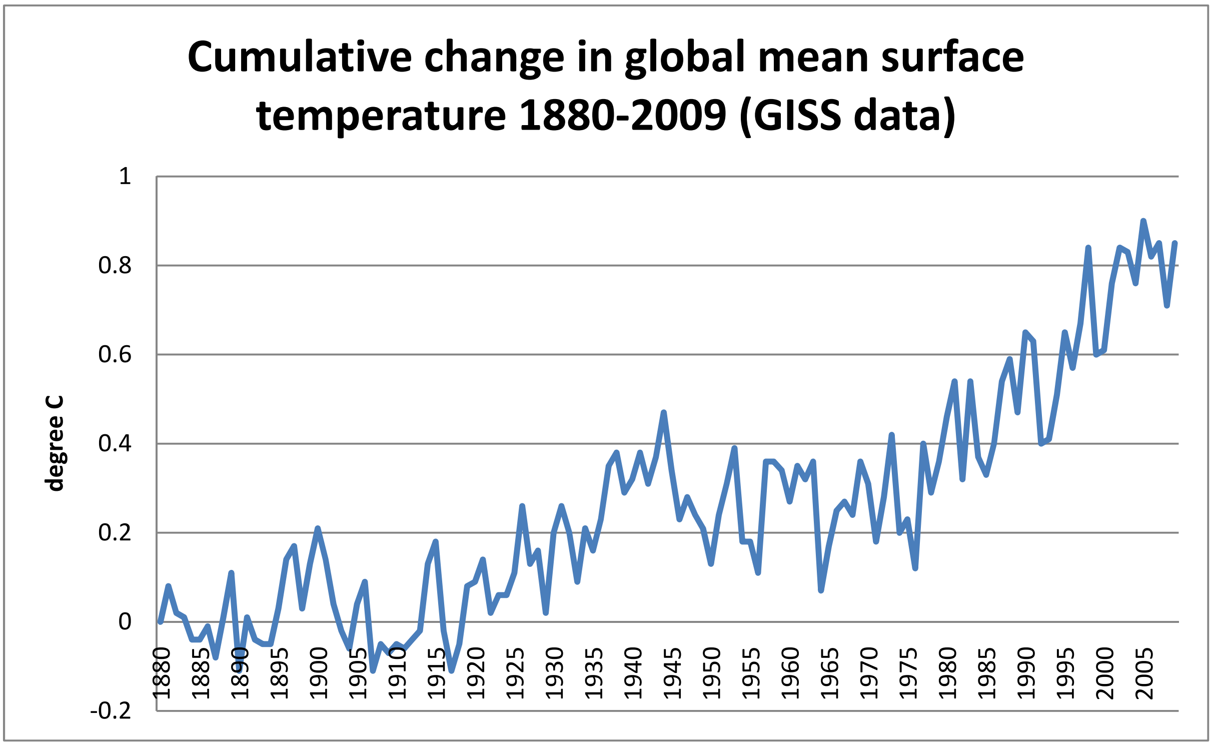
CSIRO CLIMATE SCENARIOS AVAILABLE

Scenario	Scenario variants	Period	Data source	Hypothesis tested	Issues with test
Historical climate scenario (A)		1895 to 2006	Observed SILO Data Drill	Future is like 1895-2006	Uses as a historic baseline but includes significant CC effects in this period, hence not a 'pre-CC' baseline. Also paleo shows much greater CV possible.
Recent climate scenario (B)	112 year stochastic replicate which produces a mean annual runoff closest to that observed in 1997 to 2006	1997-2006	Stochastic generation	Future is like 1997-2006 drought sequence	This is not a CC test as it is unknown what contribution CC has made to this drought period compared to no CC effect
Future climate scenario (C)	Median of 45 variants based on 3 emissions and 15 GCMs	2030	Scaling climate input variables (rain, temp, VPD, solar Radn) to 15 GCM temp predictions	Future is like median uncertainty in emissions and GCMs	An awkward measure of 2 types of uncertainty applied to a historic baseline that already incorporates CC. Does not include known climate modes.
	2nd wettest of 45 variants based on 3 emissions and 15 GCMs	2030	Scaling climate input variables (rain, temp, VPD, solar Radn) to 15 GCM temp	Future is like wet end of range of uncertainty in emissions	An awkward measure of 2 types of uncertainty applied to a historic baseline that already incorporates CC. Does not include known

			predictions	& GCMs	climate modes.
	2nd driest of 45 variants based on 3 emissions and 15 GCMs	2030	Scaling climate input variables (rain, temp, VPD, solar Radn) to 15 GCM temp predictions	Future is like dry end of range of uncertainty in emissions & GCMs	An awkward measure of 2 types of uncertainty applied to a historic baseline that already incorporates CC. Does not include known climate modes.

2. Make use of the historical climate change record

The figure below shows the global warming that has occurred since 1880. Around two thirds of the warming has occurred since 1970. Given that there are good records of climate in the MDB since the 1890s, it would be worthwhile spending some effort assessing what have been the effects of global warming to date. The IPCC for example is very reliant on its assessments of observational records.



3. **Use best available knowledge of climate change features in a climate risk framework**

A basic climate risk framework is presented in the table below. The table is divided into ‘hazard’, ‘probability’ or ‘likelihood’, and consequence. The ‘risk’ is the multiplication of these factors. The current projects are focussing on ‘consequences’ primarily, and relying on a description of climate ‘hazard’ and ‘likelihood’ as inputs.

I have also used three drivers categories (atmosphere, water, landscape), recognising we are viewing ‘climate change’ as changes in the whole ‘climate system’, not just the atmospheric component. The water and landscape drivers are only considered in the climate change context, but some projects may wish to include other factors affecting these (e.g. policy, markets). I note this is a simplification given that in this complex system there are many complex interactions and feedbacks.

Under the ‘hazards’ I have listed some of the features of climate change that are likely to affect water quality, salinity, ecosystems and people/communities/industries. I have had a very quick –top-of-the-head’ go at assigning probability and consequences.

CLIMATE CHANGE RISK FRAMEWORK

Hazard		**Probability of occurrence**	**Consequence**			
CC Feature	**Specific aspects**		**Water quality**	**Salinity**	**Ecosystems**	**People/industries**
Atmospheric drivers						
Greenhouse gases	CO2 fertilisation	High			H	
Temperature	Increasing mean temperature	High	H		H	H
	Changing max/min temperatures	High	M		H	H
	Changing frosts	High			M	H
	Heat waves	High	M		M	H

Rainfall	Increase/ decrease amount	Medium	H	H	H	H
	Rain - seasonal changes	Medium	M	L	H	M
	Rainfall intensity	High	H	L	M	M
	Rainfall – storms, cyclones	Medium	H	L	H	H
	Hail storms	Medium				H
Snowfall	Amount decline	High			M	H
	Area decline	High			M	H
Incident radiation	Net radiation increase	High				
	UV increase	High?			H	H
Humidity	Vapour pressure deficit increase	?				
	Relative humidity decrease	?				
Wind	Wind run	?				
	Wind gusts	?				
Droughts	Frequency increase	High	H	H	H	H
	Intensity increase	High	H	H	H	H
	Duration increase		H	H	H	H
	Spatial coverage increase		H	H	H	H
	Rainfall characteristics change		M		H	M
Wet sequences	Frequency, duration or intensity increase		H	H	M	H
Aerosols / Dust / VOCs						
Hydrology/Water Drivers						

Soil moisture	Drier soil profile	High				H
	Drier spatial extent	High				H
	Drier seasons	?				H
Evaporation	Higher potential evapotranspiration	High			H	
	Higher potential for canopy/understorey/litter interception loss	?				
	Higher potential for evaporation from soil profile	High				
	Higher potential for evaporation from artificial storages	?				H
	Higher potential for evaporation from natural water surfaces (eg wetlands)	?			H	
Ground water	Reduced recharge	?	L	H	M	H
	Reduced discharge	?	H	H	M	L
	Lower water tables	High		H	H	H
Streamflow	Less runoff	Medium	H	H	H	H
	Less catchment yield	High	H	H	H	H
	Altered flow regime	High	M	L	H	M
	Reduced minimum flows	Medium	H	H	H	L
	Larger flood magnitude	Medium	H	H	M	H
	Reduced flood frequency	Medium	M	M	H	M
Landscape Drivers						

Bushfires	Increased frequency	High	H		H	H	
	Increased intensity	High	H		H	H	
	Increased spatial coverage	High	H		H	H	
	Vegetation structure and composition change	High			M		
	Changed water yield (increase then long term decrease)	High	H		H	H	
Land use change/land cover change	Clearing of native vegetation feedback on climate	High			M	M	
Irrigation areas	Reduced evaporative surfaces	High					

4. Use a combination of approaches

A sensible combination of approaches would for example be to use the 5 CSIRO-MDBSYP scenarios to provide an upper and lower bound for each of the hazards and likelihoods identified in the risk table above. These would then be used to assess consequences and overall risks.

To regionalise this assessment, each region would require a separate risk table.

Each project would be able to prioritise the risks that it addresses.

Those projects that require actual scenario flow or recharge data would be able to use the CSIRO MDBSYP data that best represents the upper and lower bounds.

The risk table is also a good way of thinking through the literature review, and potentially identifying gaps in knowledge.

Appendix F Initiation Workshop Issues Paper

Requirements of the Brief

The *Water Act 2007* specifically requires the identification of risks to the condition, or continued availability, of the Basin water resources. Climate change has been identified as having probably the **greatest future impact on water availability** in the Basin. While the broad impacts of climate (eg seasonal variations in rainfall and temperature) on the Basin are expected to be addressed in phase 2 of the South Eastern Australian Climate Initiative (coordinated by the MDBA), it will not include the direct and indirect impacts of climate change on water quantity and quality per se. A number of real and potential risks to the quantity and quality of the Basin's water resources have been identified. The risks are complex and their impacts vary across the Basin. **The interactions between risks, their cumulative impacts and effectiveness of current actions need to be better understood.** Strategies for addressing or managing such risks will need to be developed, while new and emerging risks are also identified and assessed.

The Risk Assessment Program within MDBA's NRM Division is seeking to initiate the investigation of a range of such risks. These can be broadly clustered into: **risks driven by climate change (eg drought, bushfire, salinity dynamics)**; risks relating to catchment processes (eg forest hydrology, afforestation, invasive species, floodplain dynamics, land use); and risks arising from direct water interception and use (eg farm dams, stock and domestic, current management arrangements). The first cluster will comprise three synthesis reports, covering the direct impacts (through altered temperatures and rainfall), and the indirect impacts (through altered flow regimes) of climate change on the Basin's a) water quality, b) aquatic ecosystems, and c) the people, communities and industry.

Issue 1: Climate scenarios

The brief specifies that the group of climate-related projects are to use the same range of three climate scenarios in their study, namely:

A. A 'most favourable 2030 scenario' that is based on a continuation of the long-term (1895 to 2006) averages for rainfall and runoff across the MDB,

B. A 'medium 2030 scenario' that is based upon the medium global warming scenario and associated rainfall and runoff described in the CSIRO report "Water Availability in the Murray Darling Basin" of October 2008, and

C. A 'least favourable 2030 scenario' that is based upon the actual climate of the MDB in the period 1997–2006 (this includes 15% less rainfall and 50% less runoff in the southern MDB when compared with the long-term average).

No-one has questioned the use of the proposed scenarios in the project brief. However the specification of the climate scenarios is an important step in assessing potential impacts, given the aim of these projects is to assess potential climate change impacts.

The key issues around the scenarios and their use in the projects are:

What do **policy makers and water planners/managers** need to know about future CC impacts? Essentially they need to plan for the full range of potential CC impacts. However there is considerable uncertainty about what the 'full range' is, the current level of CC impacts, and the timing future impacts may occur.

CSIRO/BOM has developed CC scenarios based on GCM simulations. These scenarios account for the differences between GCM results (model uncertainty) and differences between GHG emission scenarios (emissions uncertainty). The **CSIRO/BOM climate scenarios** to 2030 were used in the MDBSYP.

The CSIRO/BOM CC scenarios do not take into account the main drivers of **climate variability** in the MDB (e.g. ENSO, ENSO-Modoki, SAM, STR, IOD). Hence the current drought (the Big Dry: 1996-2009), which is considerably more severe than the 2030 CSIRO/BOM CC forecasts, is not incorporated in the CSIRO/BOM scenarios. Given the evidence (SEACI phase 1) that there may be a link between CC and the regional climate modes (e.g. strong correlation between global warming and intensity of STR), it could be argued that the CSIRO/BOM climate scenarios (a) do not provide for a sufficiently wide range of potential CC impacts and (b) may have a timing issue if indeed CC impacts are already somewhat stronger than GCMs suggest.

The climate scenarios presented in the project brief are not 3 climate change scenarios. Two are different **historic baselines** and one is a median climate scenario. This may mean that 'climate change' is not adequately tested. One alternative is to take the MDBSYP approach by including 3 CC scenarios plus 2 baseline scenarios. Planners however may be interested in a 'worst case' scenario, which could be derived from (a) examining the palaeo record (e.g. the '50-year drought') or (b) applying CC scenarios to the Big Dry (1996-2009) baseline. However the flow implications have not been assessed and so such 'worst case' scenarios can only be considered qualitatively.

There may be an issue that the 'historical instrumental record' already incorporates a significant amount of CC impact, particularly since the 1950s. This may be a confounding factor in 'baseline' scenarios. On the other hand, CC observations may be considerably more reliable than future projections. Hence analysis of CC impacts in the observational record could be included.

The project proposals generally do not examine all the well known **features of climate change**. There is a primary focus on rainfall-induced changes to water quantity/availability. However other direct physical impacts (e.g. temperature change, ET change, CO2 fertilisation, droughts, floods, heatwaves, storms/cyclones) and indirect physical impacts (e.g. bushfires, soil moisture, groundwater recharge, vegetation responses, land use change, other interception risks) and non-physical indirect impacts (e.g. ETS, voluntary offsets, Basin Plan, consumer preferences, new technologies) are partially or not addressed.

The **baseline** against which CC impacts are to be measured is only considered in the aquatic ecosystems proposal. In this proposal there is a request to provide modelled 'natural' pre-development flow data to assist assessments of change. The use of the 'historical instrumental climate record' could be considered as a baseline, but it does incorporate climate change since 1950. What is the baseline or reference condition is a fundamental question.

How will the projects differentiate between CC and normal CV (i.e. CV without a CC forcing)? What can be learnt from CV, especially the **Big Dry**, about future CC scenarios?

Recommendation: A separate discussion paper on the selection of climate scenarios is probably necessary. Need to ensure a sufficiently wide range is covered and common key features addressed in projects. This should be discussed at the first combined workshop. A climate scientist should attend.

Issue 2: Water scenarios

All four proposals focus quite strongly on CC impacts via the rainfall-induced impact of changing surface water and groundwater. The aquatic ecosystems project requires daily flow data from the simulations. Hence, only climate scenarios interpreted hydrologically in MDBSYP can be used, if the same set is to be used by all projects.

Hydrologists state that the hydrological impact assessment is only as good as the climate data used in the scenarios. These models account for forecast changes in rainfall and do not incorporate other CC factors (e.g. temperature, ET, CO2, bushfires). Downscaling GCMs has allowed for some interpretation of finer scale processes such as local rainfall intensity which will be valuable in qualitative analyses.

Given the concern that the Big Dry may be partially attributable to CC, hydrologists have developed water scenarios based on alternative periods of the historical record. The CSIRO has developed 2 scenarios: (i) 1895-2006 representing the instrumental record and (ii) 1997-2006 representing the Big Dry. Use of such baseline periods is another way of examining ‘different conditions’, but may not necessarily be useful for interpreting future climate change impacts. Policy makers and water planners/managers do have an interest in how to manage ‘extreme events’ such as prolonged droughts and floods, which become more severe under CC scenarios.

Impacts on groundwater recharge were simulated in MDBSYP but the groundwater report was never published (although drafted). Some more recent work on groundwater recharge has been undertaken. Groundwater impacts are important for salinity, GDEs and interactions with streamflow.

Recommendations: (1) The quantitative components of the projects use water scenarios developed from CSIRO hydrological simulations of CC scenarios in the MDBSYP. (2) The historical baseline scenarios be used to examine ‘baseline questions’ and ‘severe drought’ conditions. (3) SKM team assist in the interpretation of groundwater responses to CC. (4) Agree on a common set of CC-induced water scenario features to be examined. (5) Tackle ‘worst case’ scenarios qualitatively.

Issue 3: Land scenarios

There are two ways of considering land use change. (1) land use change as a driver – that is forecasting land use change scenarios to 2030 based on population, markets, policy etc. This was the approach taken in MDBSYP based largely on work by BRS in extrapoloating current land use trends. (2) land use change as a response – this is the approach taken by economists who have examined potential economic impacts of climate-driven water availability reductions.

The water quality project and the people/communities/industries both consider land use changes. Water quality is strongly dependent of land use as a driver. The people/communities/industries assess land use change in response to water availability (driven by CC).

The aquatic ecosystems proposal has a ‘pre-development’ scenario. This scenario is modelled and could be also considered as a ‘pre-CC’ scenario.

The MDBSYP has CC and water scenarios for ‘current development’ and ‘future development’. The future development only considered a limited number of land uses and simple assumptions.
Recommendation: Land scenarios be discussed at the first workshop to see if a common approach can be taken in all projects.

Issue 4: Geographies/regions/sites

The aquatic ecosystems proposal is restricted to up to 20 specific sites. There is a question on how these sites should be selected, how representative they will be of geographies and ecosystem sites, and how they relate to Basin planning work. A GIS presentation of results is an optional extra. The Literature Review in this project may also allow expansion of the interpretation of results.

The water quality proposal aims at a SYP regions based risk assessment for each water quality parameter and scenario. This will be augmented by 'cause and effect' arguments. This output will help focus future management of areas of most concern.

The people/community/industries project will provide a matrix of results across the MDB with more information in selected community case studies.

The salinity project will cover all regions and landforms in the basin, but greater attention will be given to known high risk areas.

Need to agree on which MDB 'regions' will be used (i.e. geographic boundaries). Current proposals as based on MDBSYP, but these have been changed in the Basin Plan?

Recommendations: (1) at the workshop examine in more detail how outputs can be represented geographically. See where there are overlaps and opportunities to integrate information. (2) Check whether the new Basin Plan regions should be adopted?

Issue 5: Risk assessments

The water quality proposal provides a clear risk assessment framework at the regional level. The salinity proposal has requested advice on the risk assessment process. The aquatic ecosystems proposal assesses risk to a limited number of species and biotic groups at a small number of sites. The People/Communities/Industries project evaluates likely adaptive responses rather than risks per se.

Recommendation: Discuss risk assessment approaches at the workshop in relation to any over-arching processes being developed by MDBA.

Issue 6: Repeatability

All the projects have allowed for 'repeatability' to be catered for in their project design. The aim is to allow relatively rapid re-assessments if/when new information/scenarios become available. The specific requirements for repeatability should be discussed at the workshop with respect to aspects such as data, methods, models, IP, public domain etc.

Issue 7: Knowledge, integration and communications

No projects currently have developed communication plans. Each project will produce a 'synthesis report' and some will produce technical reports. The Project Coordinator is required to prepare a 'combined synthesis report'.

Three projects are developing conceptual models. There may be value in considering using the same approach to conceptual model building so they could be integrated. Alternatively, as different types of conceptual models are already available, consideration could be given to developing a single over-arching conceptual model.

The brief states 'The interactions between risks, their cumulative impacts and effectiveness of current actions need to be better understood.' Interactions in the complex system are important but difficult to get a handle on. It is suggested that interactions be considered at the initial workshop but assessed in more detail at a second 'integration' workshop once literature reviews and base analyses have been undertaken.

Recommendation: (1) Communications be discussed at the first team workshop. (2) Develop a single over-arching conceptual model (3) Interactions between risks and development of a more integrated understanding be considered at the initial workshop but assessed in more detail at a second workshop.

Issue 8: Timelines

Most projects are commencing almost a month later than originally planned. Revised project schedules should be prepared. A combined timeline for all projects, including the key workshops, could then be developed and circulated. Advice will be sought from MDBA on any flexibility given the late start.

Recommendations: Team leaders provide new project schedule and the Project Coordinator produce a combined schedule for agreement by MDBA.

Appendix G Global review of climate change impacts on biotic groups

Climate Change Implications for Freshwater Fish

Tropics

- The effects of climate change on fish in the tropics and in the Southern Hemisphere have been little studied compared to temperate and polar regions in the Northern Hemisphere.
- There would appear to be a substantial knowledge gap in regards to climate change and tropical fish.
- Fish habitat in the tropics is more greatly influenced by rainfall than by air temperature as in temperate latitudes.
- Within the tropics, lakes are relatively constant environments, influenced more by biotic variables, and rivers are more seasonal and influenced more by abiotic variables. Tropical riverine fish are therefore more susceptible to climate change than lake fish, though effects will vary widely with region.

Synergistic effects of other anthropogenic influences

- Human exploitation of fish stocks, the presence of exotic species and human alteration to habitat all further confound quantification of the effects of climate change on fish. For example, more than half the fish species currently found in Nevada, Utah, and Arizona are not native to those states and exotic species are reported as causing declines for more than 25% of the fish species of the U.S.A.
- The synergistic effects of other anthropogenic influences such as pollution, eutrophication and physical modifications to aquatic ecosystems with climate change also require further attention (Xenopoulos *et al.* 2005).
- Fish are likely to be more affected by climate change than most other animals due to the influence of temperature on their metabolic rate and physiology
- Climate change may affect fish and their habitat due to global increase in surface air and water temperature, groundwater temperature, and changes in precipitation patterns, wind direction and intensity, stratification of water bodies, freeze-thaw cycles, runoff, dissolved oxygen concentrations and UV-B radiation penetration.
- These changes may alter fish thermal habitat, latitudinal distribution, altitudinal distribution, spawning success, metabolism and growth, mortality rates, the susceptibility of fish communities to invasion, and community structure
- The effects of climate change on fish will be species specific and will also vary within a species, as, for example, different life-stages respond differently to temperature change

- Effects may be seasonal and are likely to be greater at higher latitudes, especially in the Northern Hemisphere
- Effects may also be site specific, even within the same habitat type at similar latitude and altitude, due to differences such as in morphometry and nutrients
- The impacts of climate change on particular species may also be revealed over differing time frames.
- Fish species that are particularly sensitive to current autumn/spring weather conditions may exhibit impacts from climate change long after those particularly sensitive to winter conditions
- Freshwater fish can detect small differences in water temperature. Changes in temperature may result in distributional changes, either through abandonment of existing habitat, colonisation of new areas, or both contractions and expansions at range edges, as species seek suitable thermal bands.
- Climate change may therefore change large-scale distribution patterns for fish species in a predictable fashion as fish migrate along isotherms. Fish are, however, restricted to their resident watersheds, which will constrain the nature of these shifts. For example, a number of studies have estimated the loss of habitat for various cold-water species in streams based on a range of possible summer maximum temperature increases. All predicted substantial losses of suitable habitat.
- Rahel (2002) predicted that a 3oC increase would result in 50% loss, Meisner (1990) predicted that a 4.1oC increase for two streams would result in 30 and 42% loss, respectively, and (Rahel *et al.* 1996) predicted that an increase of 1 to 5oC would result in losses of between 7 and 76%, depending on the climate change scenario used.
- At some higher elevations cold-water species may lose downstream habitat but gain upstream habitat. Such loss of downstream habitat would not just reduce available stream habitat but would also fragment populations
- Cold-water species in lakes may be at less risk of losing thermal habitat than stream fish but significant losses are predicted nonetheless. Coldwater fish habitat is projected to be lost from almost all shallow lakes and from 45% of all lakes in the contiguous United States under a doubling of CO2 climate scenario. Cool-water fish habitat may be lost from up to 30% of locations.
- By contrast, warm-water fish habitat will be increased. In very deep lakes all fish may experience increases in suitable habitat, indeed cold-water species may benefit the most
- Lakes that do retain suitable thermal bands for cold-water species, however, may lose vital foraging zones.
- Change in area of suitable habitat may also be driven by other effects associated with temperature increase such as increased hypoxia and altered stream flow and light attenuation. Such factors may have non-additive effects, meaning that it is insufficient to examine increased temperature alone.
- Increased temperature may initially expand suitable habitat for certain species but then a threshold of unsuitable conditions may subsequently be attained.
- Deepwater lakes are more likely to retain habitat for cold-water species, though much of very deep lakes may be below the thermal limits for all fish species most of the year

- Most freshwater fish occur at low to middle latitudes and cool-water and warm-water species may expand their ranges at higher latitudes as global warming increases habitat availability.
- Overall, species diversity and productivity in temperate regions will most likely increase but this may destabilise many temperate communities.
- Likelihood of successful invasion and colonisation is not, however, simply related to temperature increase. Changes in rainfall patterns, storm events and flow regimes will affect spawning success and recruitment. This in turn will affect invasion success. For example, in the United States rainbow trout *Oncorhynchus mykiss* invasion success at a number of locations is best explained by relative timing of flood disturbance and fry emergence. In those environments winter flooding and low summer flows favour trout recruitment.
- Altered rainfall patterns will have differing effects on fish depending on location and the position of species in the “hydrologic landscape”. Reduction in precipitation in already water-limited aquatic ecosystems in arid areas may threaten species, many of which are already rare and endangered . Conversely, increased rainfall may disrupt the spawning habits of many species that require shallow reaches as nurseries . Recruitment failure of brown trout *Salmo trutta* in Norway has been linked to accumulated snow depth in spring. Increased precipitation falling as snow, therefore, may also be detrimental to recruitment .
- Shallow spawning species can be affected by increased UV-B radiation, which may cause severe damage to eggs at depths of less than one metre in lakes with low dissolved oxygen concentrations.
- Conversely, demersal spawners may also be adversely affected if the temperature-oxygen squeeze is exacerbated, particularly if seasonal turnover of bottom water is prevented by high surface temperatures.
- Most studies of climate change on fish, however, have examined summer temperatures despite projections that some regions will experience the greatest temperature increases in winter, when many fish spawn. Certainly fish that spawn at temperatures close to their upper lethal limit appear most sensitive to change.
- Climate change will alter growth rates and productivity. Changes in water temperature affect yearling growth and prey consumption but the effects will be species specific, determined by prey availability and potential behavioural thermoregulation. Warm-water species will benefit from temperature increases but cool-water and coldwater species will likely suffer decreasing recruitment.
- Warming results in an earlier onset of stratification, a warmer epilimnion, a larger thermal gradient, and a shallower thermocline. Warmer epilimnetic water reduces littoral feeding areas for coldwater species and may result in energy intake being insufficient to initiate gamete production.
- Changes in stratification will change the distribution of prey fish species due to greater dispersal through the water column, decreasing predator-prey encounter rates. Whether this results in an increase or decrease in growth will depend on prey population sizes and the biology of the piscivore in question, though prey species may also decline in numbers.
- Negative impacts from climate change may severely reduce populations of certain species, even to the extent of local extinction.

- (For example, Jackson and Mandrak (2002) estimate that range expansion by smallmouth bass *Micropterus dolomieu* may result in the loss of more than 24,000 local populations of four species of minnow due to increased predation.)
- Changes in discharge are also likely to cause extirpations and possibly extinction in the case of highly endemic species.
- Xenopoulos *et al.* (2005) predict that by 2070, discharge will decrease by up to 80% in 133 rivers globally. Of these, 25% are projected to lose more than 22% of their fish species. These predictions do not include the additional impacts of possible decoupling of life cycles from habitat components such as floodplains and riparian vegetation. And when combined with human water consumption, rivers with reduced discharge could lose up to 75% of local fish species.
- Loss of species or significant changes in population size and growth rates will affect food web dynamics through changes to interspecific interactions. Changes in predatory fish populations will alter trophic structure and productivity and cascade down through food webs. In addition to causing the loss of prey fish species, invasive predators such as smallmouth bass can alter the behaviour of benthic invertebrates and other fish species, resulting in increased biomass of filamentous algae due to reduced grazing, or in prey ratio shifts in other predatory fish such as trout. Increases in some non-piscivorous species may reduce the abundance of large zooplankton species and increase phytoplankton biomass. This will alter the N:P ratio as well as concentrations of carbon in the water column. Loss of invertebrate taxa susceptible to increased water temperatures, however, may also impact upon many omnivorous fish species.
- Changes in flow will increase the likelihood of toxic algal blooms and of secondary infections of fish.

Climate Change Implications for Riparian Vegetation

- Riparian vegetation, like other plant communities, is subject to climate change effects such as advancement of flowering phenology and large-scale changes in distribution. However, it also subject to a large number of the indirect effects related to hydrological processes.
- Riparian zones are well recognised for their importance to aquatic ecosystems and are considered the most diverse and dynamic of non-marine habitats. They act as interfaces between terrestrial and aquatic ecosystems and regulate energy, material and organism transfer. They are influenced by precipitation, runoff and evapotranspiration. Evapotranspiration is itself governed by vegetation, humidity, temperature, wind and radiation. Riparian vegetation, therefore, has a feedback effect on the hydrological cycle.

- Riparian vegetation is linked to aquatic ecosystems by stream bank stabilisation, sediment and nutrient trapping, and the provision of shade, leaf litter and coarse woody debris. This affects fish and aquatic macrophytes, epiphytes, macroinvertebrates and vertebrates. Terrestrial vertebrates are also affected. For example, although riparian vegetation occurs on less than 1% of the western USA it supports more breeding bird species than any other vegetation type in the region. Many other species rely on it during migration.

- Climate change may increase precipitation variability, including the frequency of large storms which can alter the geomorphology of streams. Such events may be damaging but also provide opportunities for recruitment for some tree species.
- The frequency and severity of disturbances influence successional stages of riparian zones and altered hydrology due to climate change will result in changes to riparian plant communities due to variation in water availability, nutrient exchange and litter mass. Litter accumulation affects riparian plant density and biomass.
- Reductions in discharge may also make former river bottom substrates available for colonisation, though not all species will be able to do so.
- Climate change may also result in riparian vegetation being more fire-prone by decreasing fuel moisture levels. This may occur even where precipitation increases if there is greater evapotranspiration, increased temperature and changes to the timing of precipitation. There may also be an increase in the number of natural ignition events, such as lightning. Increased incidence of fire will change the input of woody debris in rivers and streams.
- Riparian zones are more prone to invasion by exotic plant species than other habitats, partly because of their linear structure, and climate change may facilitate invasion. The composition and density of riparian vegetation is important as it increases the heterogeneity of water flow patterns, increases siltation over coarse sediments modifying moisture levels in the substrate, dissipates the kinetic energy of floods, attenuates inputs to floodplains, delays drainage from backwaters, stores water (by absorption by vegetation), filters water from adjacent habitats, cycles nutrients, and is a source of carbon via decomposition.
- Loss of riparian vegetation increases UV-B radiation penetration, affecting plankton and invertebrate species composition.

Climate Change Implications for Aquatic and Emergent Plants

- Freshwater macrophytes include aquatic (in-stream and submerged), emergent and seasonally inundated species, such as on floodplains.
- Changes in water level and variability and to flow regimes will have significant effects on many species.
- Altered precipitation, especially the return period of extreme events that cause floods, will result in shifts in floodplain boundaries.
- Changes in water depth, water table height, and soil moisture and temperature partly determine the density, composition and productivity of emergent plants in wetlands. For example, reduced water levels increases dominance of deep-rooted emergent species.
- The impact of climate change will be species-specific and vary with wetland type. Wetlands fed primarily by rainfall, bogs, are more susceptible to evapotranspiration than marshes, swamps and fens, which are fed with runoff as well as rain. There may be periods when regions experience decreased rainfall with increased temperatures to the extent that evapotranspiration is greater than rainfall, causing extreme drying of wetland soils. Reduced soil moisture and increased soil oxidation would affect wetland vegetation.
- Carbon and nutrient cycles may be intensified by alterations to productivity and to decomposition and evapotranspiration rates, reducing long-term nutrient and carbon storage. Increased precipitation, on the other hand, could result to greater frequency of flushing events, which means that nutrients and organic matter may not be present long enough for efficient decomposition.

- Changes to wetland chemistry, combined with lengthened growing seasons, CO_2 fertilisation and the effects of increased UV-B radiation, will alter species composition, community structure and productivity.
- Aquatic macrophytes are affected by stream flow, local topography, channel morphology, substrate, water quality, climate, and disturbance history. They in turn modify river flows and trap sediments and provide substrate for periphyton.
- Changes to precipitation, runoff and evaporation rates will affect aquatic macrophytes with important flow on effects to food webs in rivers, streams and lakes. For example, in lakes periphyton competes with phytoplankton for nutrients taken from the water rather than the sediment. Macrophyte abundance may hence limit phytoplankton and trigger shifts to a clear-water state.
- Increased temperature and earlier growing seasons in temperate regions may increase the biomass and distribution of macrophytes in lakes, changing both the structure and ecosystem function. Changes will be most pronounced in shallow lakes.
- In addition to increasing the rate of evaporation and lengthening growing seasons, increased temperature will affect distributions. Although many aquatic macrophytes are very widespread, temperature is still a limiting factor. Many species are aggressively invasive and easily naturalised and seeds may be wind-dispersed or transported large distances by waterfowl. Warming may also facilitate the invasion of exotic tropical and subtropical tree and shrub species in wetlands in subtropical and temperate regions.

Climate Change Implications for Waterbirds

The term waterbirds typically applies to waterfowl and various waders such as herons, plovers and sandpipers. Birds dependent on freshwater habitats beyond a source of drinking water, however, include a range of species far beyond these groups. For example, 23 of Australia’s 80 bird families contain some species that are dependent on freshwater ecosystems for breeding and/or food resources. Another six families contain species that are largely dependent on riparian vegetation for foraging and nesting or sandbanks and mudbanks for nesting. Many other parts of the world also have highly specialised instream foraging species such as dippers (*Cinclus* spp.).

- The most obvious impacts of climate change on freshwater-dependent birds are changes to timing of migration and breeding, availability of suitable foraging and/or breeding habitat, and distribution. Studies into the impacts of climate change on freshwater species have mainly focused on species more typical of open habitats such as waterfowl and sandpipers and have neglected species dependent on forested streams and wooded wetlands.
- Changes in water depth, which influences movements of waterfowl, especially species that feed by diving or up-ending, means that the incidence of rainfall-related mass movements may increase. Decreased water levels encourage emergent vegetation, which in turn decreases habitat for waterfowl but increases habitat for rails and other species. Reductions in water level also increase access by terrestrial predators such as foxes, and reduction in suitable habitat concentrates populations, increasing the likelihood of disease epidemics.
- Potential distributions of birds generally may shift by more than 1000 km, which may remove species from habitats that are currently protected.
- Increased temperatures may also contribute to the establishment and spread of exotic waterfowl, many of which originate in subtropical and tropical regions and whose populations are limited by winter severity.

- Detection of changes in populations in response to climate change is more difficult than identification of phenological change. Changes in the timing of movements are readily identified from long-term data sets but the changes do vary with species and life history. A study of 24 Australian species found that arrival dates had advanced by an average of 3.5 days per decade since 1960. Departure dates were postponed by an average of 5.1 days per decade. Changes in arrival dates were greater for long-distance migrants but departure dates changed most for short-distance migrants. Long-distance migrants had not, however, altered the duration of their stay, just the timing. In contrast, North American short-distance migrants appear more likely to arrive early on their wintering grounds than long-distance migrants. This may be due to the former relying on meteorological cues rather than photoperiod, as do the latter. Some short-distance migrants have also begun to winter on their breeding grounds.
- Species that already over-winter and suffer increased mortality during severe winters may show population change if winters become less variable. Species that continue to migrate, however, may face increases in the distance they have to migrate to reach suitable conditions.
- Waterfowl eat zooplankton, macroinvertebrates and macrophytes. Indirectly, climate change may affect water-dependent birds through changes to such food resources.
- UV-B radiation and increased temperatures and evaporation may have detrimental effects on macroinvertebrates and macrophytes. UV-B radiation affects invertebrate mortality and plant growth and increased evaporation concentrates salts, changing both plant and invertebrate communities.
- Waterfowl face greater interspecific competition in winter when resources are limited, however, and increased temperatures may increase food resources and reduce competition.
- Salt intrusion into coastal wetlands due to sea level rise may also change waterbird communities.

Figure 5 Proposed project timeline

		March	April	May	June	July	August	September		October		November	
								mid	end	mid	end	5 11	
1	**Project initiation**												
	Project kick-off meeting and contract signing												
2	**First meeting of all project teams**												
	Meeting preparation and organisation												
	Meeting & follow up												
3	**Monitoring of research progress, resolving issues**												
4	**Review of submitted literature reviews**												
5	**Review interim findings**												
6	**Variation to incorporate synthesis of 7 projects**												
7	**Review draft reports**												
8	**Final meeting of all project teams**												
	Preparation												
	Meeting												
	Follow up												
9	**Prepare draft synthesis report**												
	Synthesise 7 reports & embed in current knowledge												
	SKM practice review												
10	**Finalise report**												
	Submit draft synthesis, summary, communications plan												
	Revise with comments from MDBA												
	Present results to MDBA												