Australian Government
Land & Water Australia

research report

knowledge for managing Australian landscapes

Climate change and water use of native vegetation

Cate Macinnis-Ng and Derek Eamus
University of Technology, Sydney

UNIVERSITY OF TECHNOLOGY SYDNEY

Number 5 in a series of 6

About the authors

Cate Macinnis-Ng

A research fellow in plant ecophysiology in the Plant Functional Biology and Climate Change Research Cluster at the University of Technology, Sydney, Dr Cate Macinnis-Ng has a research focus on plant water use and productivity. Recent research has included quantification of ecosystem water use in remnant vegetation and application of a soil-plant-atmosphere model to investigate interactions.

Derek Eamus

Derek Eamus is Professor of Environmental Sciences at the University of Technology, Sydney. A Land & Water Australia senior research fellow, he specialises in the study of the ecohydrology of Australian landscapes, including the measurement and modeling of landscape water and carbon fluxes, the influence of climate change on forests and the function of groundwater dependent ecosystems.

Published by: Land & Water Australia, June 2009

Product Code: IDPN30134

Print ISBN: 978-0-9806611-8-7

Electronic ISBN: 978-0-9806611-9-4

Postal address: GPO Box 2182, Canberra ACT 2601

Office Location: Level 1, The Phoenix

86–88 Northbourne Ave, Braddon ACT

Telephone: 02 6263 6000

Facsimile: 02 6263 6099

Email Land&WaterAustralia@lwa.gov.au

Internet: lwa.gov.au

Disclaimer

The information contained in this publication is intended for general use, to assist public knowledge and discussion and to help improve the sustainable management of land, water and vegetation.

To the extent permitted by law, the Commonwealth of Australia, Land & Water Australia (including its employees and consultants) the authors, and its partners do not assume liability of any kind whatsoever resulting from any person's use or reliance upon the content of this publication.

For further information contact Derek Eamus, Professor of Environmetnal Sciences, University of Technology, Sydney
PO Box 123, Broadway, NSW 2007. www.c3.uts.edu.au

Key points

Under climate change conditions Australia will generally be hotter and, for many parts of the country drier.

Vegetation water use is strongly influenced by soil moisture availability (which is influenced by rainfall) and evaporative demand.

Soil moisture will be more scarce in the future across much of the continent due to declining rainfall.

The major input of water into the Australian landscape is rainfall and most rainfall (70–95%) returns to the atmosphere as evapotranspiration, leaving little water for human consumption, riverflows and recharge of groundwater.

The proportion of rainfall used in evapotranspiration increases as rainfall declines so even though the absolute amount of transpiration may decline, the water yield of a landscape will also decline as rainfall decreases with climate change.

Whole tree growth chambers are used to study tree responses to CO_2 enrichment in the Hawkesbury Forest Experiment

Climate change—what is it and what causes it?

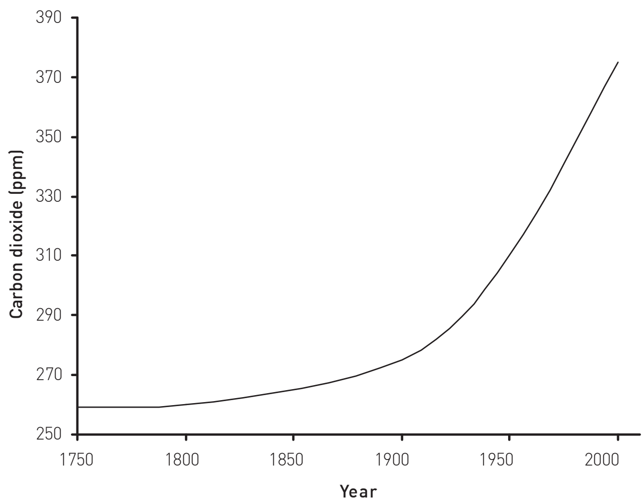
The term "climate change" refers to any change in climate over time, whether due to human activity or as a result of natural processes. However, a comparison of climate change that occurred in the geological past (thousands to hundreds of millions of years ago) with the recent past (since the industrial revolution of the 18^{th} century) shows that as the world has become industrialised, human activities have had a much greater impact on climate fluctuations than natural variation. Data from ice cores spanning many thousands of years indicate that global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased significantly since 1750. Increases in atmospheric carbon dioxide are primarily due to burning fossil fuels and land use change (particularly deforestation) while agricultural activities have stimulated the production of methane and nitrous oxide.

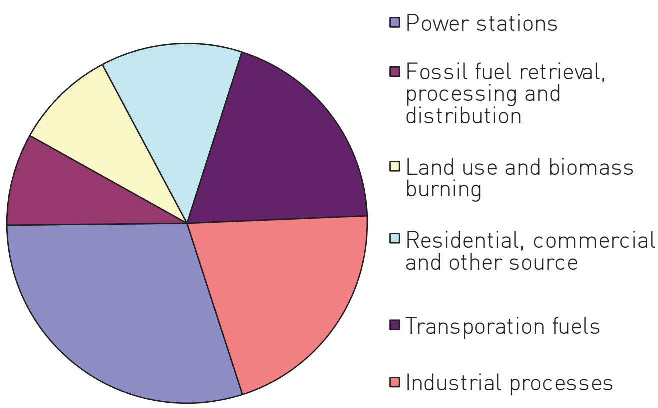
The impact of these greenhouse gases is to warm near-surface global temperatures through the greenhouse effect. Greenhouse gases absorb incoming short-wave solar radiation and emit long-wave radiation which warms the atmosphere and the earth's surface. This process is essential to maintaining the relatively warm, inhabitable temperatures of the earth. Indeed, in the absence of these greenhouse gases, the world's average temperature would be below 0°C. When concentrations of greenhouse gases increase, global temperatures increase.

As a consequence of increases in atmospheric greenhouse gases, the earth's climate is changing. Examples of climate change which have been recorded include global warming, indicated by increasing global average air and ocean temperatures, extensive melting of snow, glaciers and polar ice caps and rising global average sea level. Perturbations in precipitation (the amount, the timing and the spatial distribution), wind patterns, and increased frequency of extreme weather events such as droughts, heat waves and intense cyclones have also been observed.

Atmospheric concentrations of greenhouse gases can be converted to values of radiative forcing, where positive forcing causes warming while negative forcing causes cooling of the atmosphere. Global climate models are mathematical representations of the physical and biophysical processes driving the Earth's climate. Climate models use values of radiative forcing to predict climatic changes according to various emissions scenarios. For instance, for a range of emissions scenarios, global air temperatures are expected to rise 0.2°C for each of the next two decades and even if atmospheric concentrations of all greenhouse gases had been maintained at 2000 levels, a warming of 0.1°C would be expected for each decade. Patterns of precipitation, wind and extreme weather events can also be modeled with regional scale models to project the finer implications of climate change.

There is abundant observational and projected evidence to suggest that freshwater resources are highly vulnerable to climate change impacts, particularly in dry environments because dry ecosystems are more responsive to changes in atmospheric CO_2, temperature and precipitation.





Approximate concentrations of atmospheric CO_2 and sources of atmospheric CO_2 in 2006. Pre-1950 data were measured from ice cores. Redrawn from Garnaut (2008) and CSIRO (2007).

Key aspects of climate change for Australia

Average Australian temperatures have increased 0.9°C across the continent since 1950. The frequency of cold days and nights has declined while the frequency of hot days and nights has increased.

Recent years have been unusually dry in south-west and eastern Australia while most of north-west Australia has become wetter since 1950, with greater increases in rainfall during summer months. Over the last 50 years, north-western and central Australia and the western tablelands of New South Wales experienced increased extreme rainfall. In contrast, these conditions have decreased in areas in the south-east and south-west and along the central east coast.

Future changes in climate depend on global levels of emissions of greenhouse gases. As described above, gas emission scenarios are fed into climate models to produce projections of likely climate conditions. Variations in projections therefore arise from the range of emission scenarios used and also the uncertainties associated with each particular climate model. The efficacy of each model can be confirmed by using historical data to confirm the success of the model so scientists can quantify the likelihood of particular projections and therefore be confident in the data produced. Generally, in this document, we have reported the published mid-point of spread and range of model results (CSIRO, 2007).

Across Australia, air temperatures will rise about 1°C (range 0.6 to 1.5°C) above 1990 levels by 2030, based on mid-range emission scenarios. There will be seasonal variation with slightly more warming in summer than winter and there will be a little more warming in inland areas compared to coastal areas. By 2070, annual air temperatures will be elevated by 1.8°C for low emissions and 3.4°C for high emissions. Associated with this, there will be more days with temperatures above 35°C and fewer frosts.

There is significant natural variability in recorded rainfall on the decade-scale and this is because of the major impact of El Niño and La Niña cycles on Australian rainfall. Consequently, modeling rainfall patterns is more complicated than modeling temperature. Fluctuation in rainfall due to droughts may mask or enhance changes in rainfall induced by the greenhouse effect. Rainfall is projected to increase and decrease for different models at many locations across the continent. Changes in rainfall due to climate change are also seasonally variable so while there may be very little change in annual rainfall arising from climate change, the seasonal distribution of the rainfall is predicted to change in many models of Australian climate. This is the case in the eastern states where there may be an increase in summer rainfall but a decrease in winter rainfall. For the high emissions scenario, the annual rainfall change is projected to be -30 to +20% by 2070 across the entire continent. Decreases in rainfall are most likely to occur in the south and west of the continent while increases are most likely in the northern and eastern areas. An increase in rainfall intensity (volume of rainfall in a day) and number of dry days is also projected.

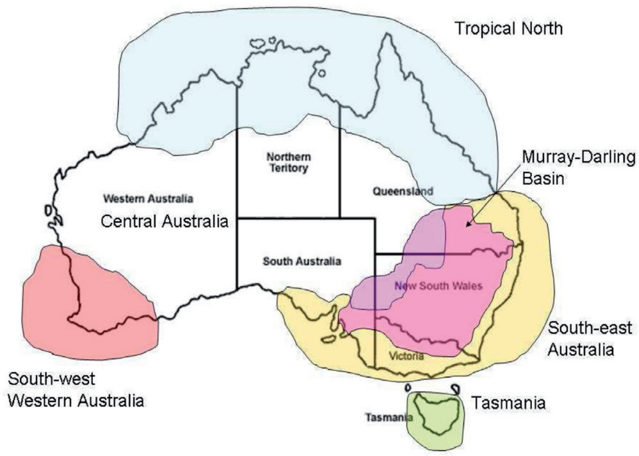
Small decreases in relative humidity are projected for most of Australia. By 2030, this decline will be approximately 1%, with the largest decreases being in the south and west and little change on the east coast, which is a similar pattern to rainfall changes. This may increase to up to 4% in the south and west by 2070 for the high emissions scenarios.

Evapotranspiration is the sum of water lost from soil, vegetation and water bodies through evaporation from wet surfaces and transpiration through leaves. Potential evapotranspiration is the amount of water lost when all surfaces are saturated, calculated from air temperature, relative humidity, downward (incoming) solar radiation and a vapour transfer coefficient. Potential evapotranspiration is a measure of the evaporative demand of the atmosphere and has a significant impact on the water balance of landscapes. It is projected to increase over much of the continent, particularly in the north and the east due to increases in air temperature and decreases in relative humidity. In some of these parts, potential evapotranspiration may increase by up to 16% by 2070 for the high emission scenario.

Soil moisture is likely to decline in southern Australia due to changes in rainfall and increases in evaporation. There will be up to 20% more drought months over most of Australia by 2030. A drought month is defined as having very low soil moisture (the driest 10% for the period 1974-2003). This will rise to up to 40% in eastern Australia and up to 80% in south-western Australia by 2070. These warmer, drier conditions will also increase the number of very high fire danger days, lengthening the fire season. More intense weather systems will also stimulate storm surges and the intensity of tropical cyclones will increase.

Likely climate changes in key regions of Australia

Australia has a diverse range of climate zones, ranging from hot humid in the tropical north to cool temperate in Tasmania. The large differences in temperature and rainfall between the north and south of the continent mean that Australia has a highly diverse range of environments. The main climatic zones are shown in below.



The major climate regions of Australia. These regions are: the tropical north (blue), central Australia (white), South-west WA (red), South-east Australia (orange) and Tasmania (green). The Murray Darling Basin is superimposed in pink.

The tropical North

The weather in northern Australia (including the northern-most areas of WA, NT and Qld) is typified as being hot humid and there is a distinct wet season during summer. The major vegetation type is tropical savanna, also known as open Eucalypt forests and woodlands with a grassy understorey. Open forests (with 30-70% foliage cover, 10-30 m tall) dominated by *Eucalyptus tetrodonta* cover the northern-most areas of NT and Qld and further south, woodlands (10-30% foliage cover, 5-10 m tall) are more prevalent. The understorey is usually grassy with a midstratum of Acacia in some areas.

The vegetation is fire tolerant with rapid regeneration and regrowth after a fire from underground organs (lignotubers), seeds and epicormic buds. Climate change will cause higher temperatures and lower relative humidity but little change to rainfall.

Central Australia

This region covers the largest land area, including most of WA, the south of the NT, most of SA and western Qld and western NSW. The climate is arid with low rainfall throughout the year and summers are very hot and dry. The northern areas of this region have a warm winter while winters become cooler further south. The vegetation is predominantly hummock grasslands, Acacia shrublands with some areas of low lying Acacia forests and woodlands. Hummock grasslands are dominated by large hummocks of desert spinifex grasses belonging to the genera *Triodia* and *Plectrachne*. The hummocks cover 10-30% of the soil with bare spaces between, sometimes interspersed with low shrubby trees from the Acacia, *Allocasuarina, Eucalyptus, Grevillea* and *Hakea* genera. Central Australia will become hotter and drier as climate change progresses.

South-west Western Australia

The climate of south-western WA is classified as "Mediterranean" meaning that rainfall is winter dominant and temperatures are warm to hot all year. There has been a significant decline in rainfall in this region since the mid 20th century for the months May, June and July, resulting in a 50% reduction in annual inflows to reservoirs supplying Perth. This is associated with a 20% increase in domestic water use in the last 20 years and groundwater resources and wetlands have also been compromised. At least some of this observed drying can be attributed to the greenhouse effect. Much of this region has been cleared for agricultural purposes but there are vast areas of Jarrah forest which are classified as Eucalypt tall open forest dominated by *Eucalyptus marginata* growing up to 30 m or more with a dense understorey. Further inland, there are eucalypt open woodlands with a grassy understorey and patches of mallee open scrub. This is one of the regions which will suffer the most severe climate change. The air will be hotter and drier with less rainfall, particularly in the all important winter months.

South-east Australia

This is the temperate zone of the continent. While there is no distinct wet season, winters are wetter around Adelaide and Victoria and summers are wetter in northern and coastal areas of NSW and south-east Qld. The central zone of this region, including inland parts of eastern NSW has a predominantly uniform rainfall distribution across the year. Summers can be hot, warm or mild depending on the latitude and distance from the coast. Much of the land is cleared for agriculture but there are vast areas of Eucalypt open forest in Vic, southern NSW and along the coast to SE Qld. Patches of Eucalypt woodland remain in inland areas and there are areas of rainforest in northern NSW and southern Qld. In the coastal regions of SA, mallee open scrub occurs with multi-stemmed mallee eucalypts (foliage cover 30-70%, 2-8 m tall) with a variety of understorey species. Inland areas will be affected by climate change more than the coastal zone. Temperatures will increase in all areas, relative humidity will decline inland and rainfall will decrease across the region.

An open woodland, Liverpool Plains, NSW (Photo Mel Zeppel).

Tasmania

The Tasmanian climate is typified as cool temperate. Winter is generally slightly wetter than summer and summers are very mild. Vegetation types include rainforest and vine thickets on the west coast and Eucalypt open forest up to 30 m on the eastern side of the state. As indicated in the table Tasmania will be the area least effected by climate changes according to the current projections.

Murray Darling Basin

Australia's largest river basin accounts for approximately 70% of the nation's irrigated crops and pastures. The catchment covers parts of southern Qld, most of inland NSW, northern Vic and the area east of Adelaide. Much of the area is in the south eastern Australia region described above but about half of the catchment is in the central Australia region with much lower rainfalls. Much of the catchment is vegetated either by woodlands and open woodlands dominated by Casuarina, Acacia and Eucalyptus or irrigated pasture and cropland.

The on-going drought in eastern and southern Australia has caused the total inflow to the Murray River to be the lowest five year sequence on record for the years 2000 to 2005. By 2050, annual stream flow is projected to fall 10-25% and by 2100, it will fall 16-48% due to climate change. Due to the economic significance of this region much research has been conducted to project the impacts of climate change. The climate will become hotter and drier across most of the catchment.

Projected climate change in the main regions of Australia for 2070. Ranges incorporate variability due to different emissions scenarios. Compiled from the Climate Change in Australia Technical Report (2007) www.climatechangeinaustralia.gov.au.

Climate region	Annual average temperature*	Relative humidity	Total annual rainfall	Seasonality of rainfall
Tropical north of Australia	2.5–3°C increase	Decrease by 1–2%	Minimal change	Greater change in rain in winter and spring
Central Australia	Up to 3°C increase in most areas and 4°C in the west	Decrease by 2–3%, greater decrease in the west	5–20% decrease	Greater change in rain in winter and spring
South-west WA	2-3°C increase	Decrease by up to 3% for severe emissions scenarios	10–20% decrease	Decrease greater in winter and spring
South-east Australia	2–3°C increase in inland areas and 1–2.5°C near the coast	No detectable change in coastal areas but decrease by up to 2% inland	5–10% decrease	Increase in summer rainfall but decrease in winter rainfall
Tasmania	1–2.5°C increase	No change	About 5% decrease	Increase in winter and autumn but decrease in spring and summer
Murray Darling	1.5–3°C increase	2-3% decrease	2–10% decrease	No change in summer and autumn, decrease in winter and spring

* All areas show more warming in spring/summer than autumn/winter so summer increases are greater than the annual average.

How does vegetation use water?

Plants require water for many biochemical reactions (such as photosynthesis), for evaporative cooling, to help transport nutrients through the plant and to prevent wilting (since water helps support the plant with water filled cells). All most all of the of water absorbed by plants is evaporated from leaves (as transpiration) when leaf pores (called stomata) open to allow CO_2 to enter the leaves for photosynthesis. The degree of opening of stomata is termed stomatal conductance, where higher stomatal conductance indicates greater opening of pores and hence, greater water loss.

One of the main pathways for movement of water in the environment is known as the soil-plant-atmosphere continuum (SPAC). The SPAC represents the physical continuity of water as it moves from the soil, into roots, up the plant to leaves, then out into the atmosphere. There are many features of the plant and environment which can influence the rate of water movement through the SPAC. The easiest way to think about water flow in the SPAC is by starting at the leaves of the upper canopy and moving down the plant to the soil. If we assume the soil is moist, stomata open in the morning as the sun rises and leaf and air temperatures increase. The CO_2 concentration within the leaf declines as photosynthesis begins in response to light and this triggers the stomata to open. Before dawn, the cells of the leaf are saturated with water as the leaf has spent the night rehydrating from plentiful soil water. The water potential of the water in the cell walls is very close to zero as is the water potential of the sub-stomatal cavities, directly below the stomata. Each sub-stomatal cavity is saturated with water vapour as it is in equilibrium with the water potential of the walls of the cells lining the sub-stomatal cavity. The concentration of water vapour inside the substomatal cavity exceeds that of the atmosphere and thus, once the stomata open, water diffuses out of the leaf in the process called transpiration.

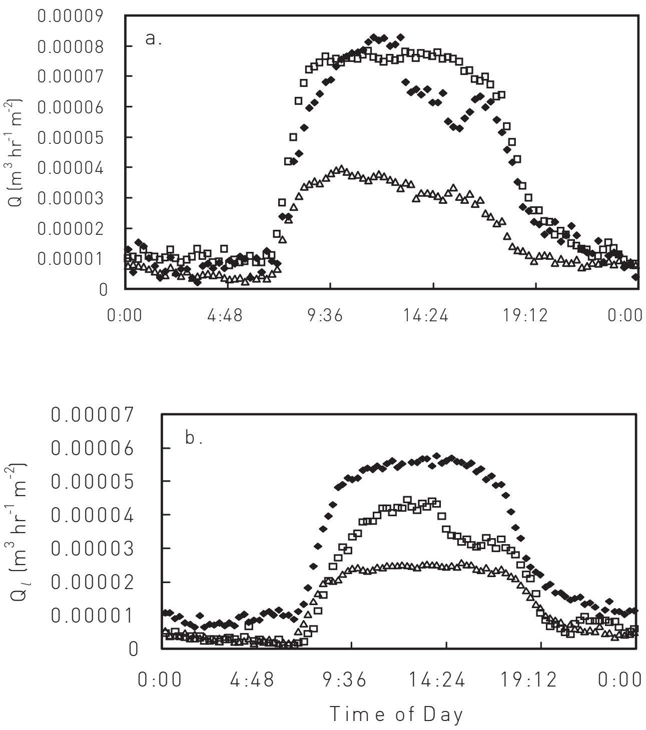
As water is lost from the sub-stomatal cavity, a gradient in water vapour pressure is created between the water at the surface of the walls of cells surrounding the sub-stomatal cavity and the cavity itself. To replace the water lost as transpiration, water evaporates from the cell walls, causing the water potential of the cell wall to decline, so water moves from cell walls further from the sub-stomatal cavity and from the cytoplasm of adjacent cells towards the sub-stomatal cavity. Thus, a gradient of water potential expands from each stoma through the leaf, eventually reaching the leaf xylem. Xylem is the term used for transport tissue responsible for transporting water and soluble mineral nutrients from the roots throughout the plant and for replacing water lost through transpiration and photosynthesis. As water is lost from the leaf xylem, adjacent water molecules are 'dragged' up the xylem network. This occurs because water has cohesive properties due to hydrogen bonds between adjacent water molecules which allow the molecules to stick together. These hydrogen bonds also contribute to the occurrence of surface tension in liquid water, allowing it to behave like an elastic sheet. This cohesion-tension theory explains how water is drawn up the xylem of the stem against gravity.

The reduction in water potential which is first observed in leaves when the sun rises, is transmitted down the plant to the root and eventually occurs in the outer epidermal cell walls of the root and into the soil around the root. Thus, the evaporation of water from the leaves causes water to enter the roots because of the gradient of water potential through the plant. This process is known as transpirational pull, the main phenomenon driving the flow of water through the xylem of large plants.

Transpiration varies according to a number of plant, soil and atmospheric conditions. Physiological adaptations of plants strongly influence the rate of transpiration. For instance, plants adapted to arid environments may have stomata in deep pores on the underside of leaves or leaves covered in hairs to reduce evaporation (and therefore conserve water). Soil properties which influence transpiration include the texture and organic content which influence soil water availability. Trees generally use more water than shrubs and grasses due to deeper roots, longer growing cycles and larger leaf areas.

Atmospheric conditions influencing transpiration change daily and seasonally. Despite the variations in physiological adaptations and site-specific environmental conditions, daily tree water use shows consistent patterns across species and around the world. This is due to the universal role of solar radiation and evaporative demand in determining vegetation water use. Water use increases after dawn as solar radiation becomes available to the canopy to drive transpiration. Rising leaf and air temperatures and increased potential evaporation rates (or increased leaf-to-air-vapour-pressure-deficit) are associated with increasing solar radiation, further accelerating transpiration through the morning, until a maximum rate of transpiration is reached. In the afternoon when solar radiation declines, evaporative demand is reduced and leaf and air temperatures decline and transpiration also gradually declines. A typical pattern of tree water use is shown below.

Seasonal variation in transpiration is usually associated with changes in water availability (soil moisture), evaporative demand, solar radiation input and leaf area. Thus greatest seasonal differences are seen at sites which have a distinct wet and dry season, such as northern Australia. Peak water use is much larger in the wet season due to more abundant soil moisture, fewer clouds to block solar radiation and a larger leaf area for transpiration.

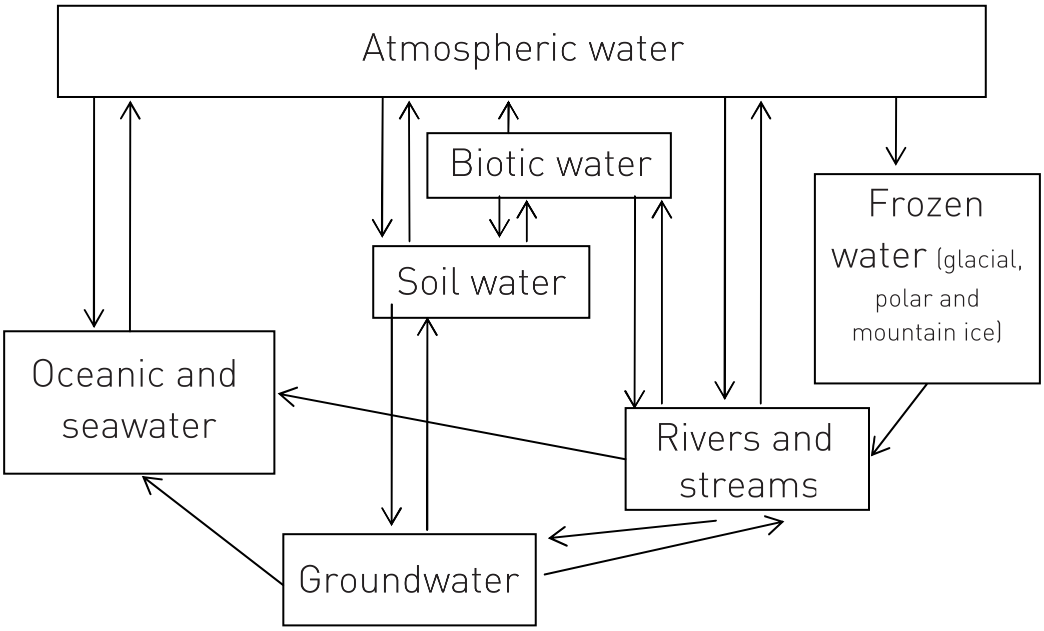


Seasonal and diurnal patterns in tree water use are strongly influenced by atmospheric conditions. Diurnal patterns of transpiration at Darwin (◊), Katherine (☐) and Newcastle Waters (Δ). Data represent the mean wet season (a) and dry season (b) transpiration rates for the two dominant species at each site over a five day sampling period. Data from A. O'Grady, Uni. Tas. Personal comment.

Role of vegetation water use in the hydrological cycle

The hydrological cycle (also known as the water cycle) is the continuous circulation of water between oceans, the atmosphere, land and vegetation. Water evaporates from the oceans, land and vegetation into the atmosphere, where clouds are formed. The water then falls as rain and returns to the land, vegetation and oceans. Thus, the main movements (or fluxes) of water on land in the hydrological cycle are precipitation (including rain, snow, mist, fog, hail) and evapotranspiration (the sum of evaporation from soil and lakes and transpiration from leaves). By far the single largest flux of water into Australian landscapes is rainfall and the largest loss from the landscape occurs as transpiration through leaves.

The hydrological cycle is a global process, generally associated with seasonal patterns of temperature and rainfall but there are several features of the Australian environment which make it distinctive. Rainfall in Australia is low (mean annual rainfall is 350 to 400 mm yr^{-1}, lower than any other continent) and highly variable between years. The atmosphere is very dry, causing high evaporative demands across much of the continent for most of the year and the continent is very flat, so cloud formation resulting from the movement of air into the upper atmosphere up the sides of mountains is minimal. There are few rivers and lakes so the main input of water in many Australian ecosystems is rainfall. Due to low rainfall, runoff is also very low across most of the continent at less than 10 mm yr^{-1}, the exceptions being in the tropical monsoonal north and areas of the east coast where rainfall is much greater. All of these factors contribute to limited water availability in the Australian environment and explain why native vegetation has many adaptations for water conservation.



The hydrological cycle depicted as movement of water through major water stores.

Accounting for the inflows and outflows of water in a region involves constructing the water balance where inflows = outflows + changes in water storage. In more detailed form, if we assume that groundwater inputs and outputs are equal, we can assume that rainfall is the only input to the water balance.

Therefore, $P = E + T + O + RO + G + \Delta S + \Delta w$

Where P = precipitation, E = evaporation from soil and from canopy interception, T = transpiration, O = overland run-on, RO = surface run-off, G = groundwater discharge, ΔS = change in soil moisture storage and Δw = change in groundwater storage. If we assume run-on and run-off are negligible on an annual time-frame, and both soil moisture storage and groundwater storage can be available to deep-rooted plants for transpiration during low rainfall periods, most water entering the system is lost as evaporation and transpiration (together, evapotranspiration).

Consequently in many hydrological models, the water balance is simplified to,

$Q = P - ET$

Where Q is the annual runoff (water yield available for river flows or human consumption) and ET is the evapotranspiration. The major component of evapotranspiration is transpiration because roots can access a much larger volume of water in the soil profile than that which can be evaporated from the surface alone. Therefore, almost all of the rainfall on a catchment can be transpired through the vegetation of that catchment and over much of Australia, transpiration accounts for between 70 and 95% of incoming rainfall. This statistic demonstrates the integral role of vegetation water use in the hydrological cycle. Furthermore, during drought conditions, the proportion of rainfall used by vegetation can increase.

Simplified site water balance for remnant native woodland on the Liverpool Plains, near Quirindi NSW in a dry year and a wet year. All values are mm except percentages in brackets which indicate the percentage of incoming rainfall. (Data: Mel Zeppel, UTS).

Year	Rainfall (mm)	Tree water use	Interception losses	Understorey water use	Total vegetation water use	Recharge
Drought year	522	309 (59%)	52 (10%)	150 (29%)	511 (98%)	11 (2%)
Non-drought year	1062	629 (59%)	106 (10%)	210 (20%)	945 (89%)	117 (11%)

Responses of leaf-scale transpiration to increased temperature, increased atmospheric CO_2 concentration and reduced rainfall

Predicting the nature of changes in transpiration in response to climate change is complex because of the interactions between different components of climate and vegetation. For instance, there is a wealth of experimental evidence that indicates that stomatal opening of plants will be reduced under elevated concentrations of atmospheric CO_2, leading to lower transpiration rates. The larger amount of CO_2 in the atmosphere means that there is more CO_2 available for photosynthesis without stomata opening so much, allowing the plant to conserve water. Yet models of atmospheric and soil water feedbacks suggest that any reductions in transpiration will be smaller than those expected because of stomatal closure alone. This is partly because temperature increases are predicted to increase transpiration, therefore having the reverse effect of elevated atmospheric CO_2 concentration and may also be because total leaf area of trees could increase in a climate change world and this tends to increase the amount of water used by a tree canopy (see below).

Warming can directly influence plants by altering photosynthesis, respiration and hence growth. It can also indirectly influence plant productivity and growth through extended growing seasons and altered plant phenology. Other indirect effects include changing spring thaw dates, increasing soil nitrogen mineralization and availability, declining soil water content and changing community structure through changing species composition. Computer simulations in temperate and tropical forests, heathlands and grasslands predict that elevated temperature will stimulate transpiration, when water availability allows this to be expressed.

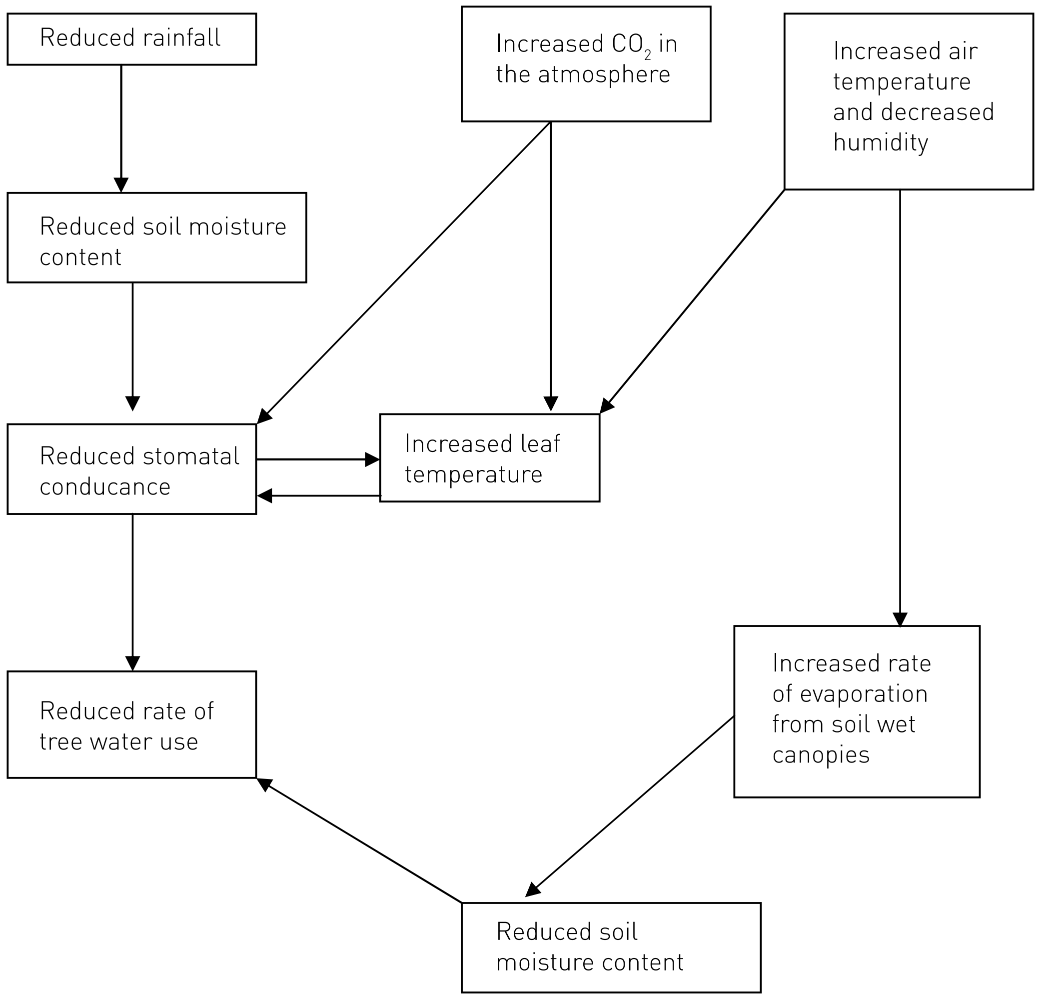
At a leaf-scale, temperature effects stomatal closure in a non-linear way, either directly or indirectly through effects of temperature on photosynthesis and respiration. An optimal temperature determines when maximum stomatal opening will occur and stomatal conductance will decrease below and above this temperature. The optimum temperature for a particular plant will depend on its physiological adaptations to the surrounding environment. Transpiration also impacts on leaf temperature through its role as a cooling process. Temperature increases above the optimum lead to reduced transpiration which in turn increases leaf temperature, leading to further stomatal closure.

Carbon dioxide is used by plants in photosynthesis to produce sugars which can be used as the raw material for making organic compounds for plant growth and development or the sugars can be used in respiration. Thus, CO_2 availability directly influences the productivity and functioning of plants, whereby elevated CO_2 concentrations stimulate faster accumulation of biomass while reducing associated water use through reduced stomatal conductance. Since less water is lost through the same stomata as CO_2 is absorbed, the water-use-efficiency (the ratio of the number of CO_2 molecules fixed by the plant to the number of H_2O molecules lost by transpiration) is higher.

The influence of CO_2 on stomatal conductance has been quantified. An analysis of the relationship between increasing CO_2 concentration and declining stomatal conductance found that for every 10 ppm increase in CO_2 concentration, stomatal conductance declined 0.68% for trees and this value was slightly larger for grasses and herbaceous plants. Therefore, grasses and herbaceous plants are more greatly influenced by increasing CO_2 concentrations than trees, possibly because the deeper roots of trees provide a buffer against changes in soil moisture due to declining rainfall.

Reduced rainfall causes less infiltration of water into the soil so soil moisture declines and there is less water available for use by vegetation. As the water potential of leaves declines with the rising sun in the morning, and the water potential through the plants declines, if the soil water potential is low due to limited water availability, the plant will close its stomata to prevent excessive water deficit. The result is reduced transpiration. The influence of declining rainfall is generally greater at drier sites as the plants may be already operating close to their limits.

Multifactor responses can differ greatly from simple combinations of single-factor responses. Experimental data examining multifactor responses are sparse so most predictions of multiple effects are based on model outputs. Differences in model structures, underlying assumptions and site specific details (such as vegetation type and annual rainfall) affect the outcomes so multifactorial influences of climate change on stomatal conductance remain unresolved.



A schematic outline of the relationships between changes in climate and tree water use

Responses of canopy-scale water use to increased temperature, increased atmospheric CO_2 concentration and reduced rainfall

Although many assume canopy transpiration to respond to climate change in a similar way to leaf-scale transpiration since the canopy is essentially a collection leaves, this assumption is generally incorrect because of the role of leaf area in determining canopy transpiration. The degree of coupling between a canopy and the atmosphere varies with leaf area index and the height of the canopy. A short dense grass canopy is relatively uncoupled from the atmosphere and changes in evaporative demand (atmospheric humidity) have much less impact on transpiration from a grass sward than the same change in evaporative demand has on transpiration from a tall, open woodland, which is more tightly coupled to the atmosphere. This section explains the impact of leaf area on canopy (and therefore landscape) transpiration and outlines predictions of climate change impacts from multi-factorial models.

As explained in the previous section, elevated concentrations of atmospheric CO_2 enhances biomass production and increases water use efficiency. A plant can therefore support more leaves on a branch supplying the same amount of water. Thus, it might be expected that a larger leaf area might be accumulated over time. Yet this leaf area should also be transpiring at a lower rate (since stomatal opening is not as great), hence the net effect of CO_2 enrichment is often much less than would be expected from consideration of the response of individual leaves exposed to CO_2 enriched atmospheres in small chamber experiments. The reason for this is that observations made at leaf-scale use chambers with a high rate of air movement to minimize the boundary layer effect of gas diffusion. In contrast, in natural ecosystems a vertical stratification of wind speed occurs, along with increasing self-shading of leaves as canopy LAI increases. Both of these effects reduce the relative response of leaves to CO_2 enrichment compared to the response observed for single leaves in well illuminated and well ventilated chambers.

Enhanced atmospheric CO_2 rarely causes increased equilibrium leaf area index (LAI), except where artificial ventilation is used in the study, such as in chambers or greenhouses. While an initial increase in LAI is often observed in the early stages of growth under CO_2 enriched conditions, this generally stabilises after several years, often returning to a similar leaf area as the control. This is because nutrient limitation (particularly nitrogen availability) in natural ecosystems limits the productivity of plants under elevated CO_2 concentrations, thereby limiting LAI increases. A possible exception to this is in arid and semi-arid zones where woody thickening may occur in response to CO_2 enrichment because of the increase in water availability arising from the increased water use efficiency generated by increased atmospheric CO_2.

The response of tree water use to changes in climate can be positive and negative. Some studies find tree water use and this is generally in environments where rainfall is increasing or where the canopy is not yet closed (young stands of trees) and LAI is stimulated in response to CO_2 enrichment. In contrast, other studies find tree water use is reduced and soil moisture content can be increased (for at least part of the year) under CO_2 enriched conditions. For much of temperate and sub-tropical Australia, the projected declines in rainfall will dominate the response of vegetation water use, although water use efficiency is likely to increase under CO_2 enriched conditions, especially where rainfall is declining.

The importance of changes in rainfall was demonstrated by a recent study which modeled the impact of halving and doubling precipitation in combination with elevated CO_2 and temperatures across seven ecosystems. When rainfall was increased, the percent change in transpiration was -10 - +40% with six of the seven sites having enhanced transpiration. Reduction in rainfall caused declines in transpiration across all sites with proportional changes varying between approximately 20 and 100%. The role of rainfall in maintaining soil moisture was highlighted as being more influential over changes in transpiration than CO_2 and temperature increases. Halving and doubling of rainfall is more extreme than the scenarios projected for Australia but the sites studied already had much larger rainfalls than those in Australia and amongst the sites studied, the driest sites were most responsive to changes in climate, individually and in combination. Thus future water availability is likely to tightly govern transpiration while physiological effects of warming and more available CO_2 will be less important influences on tree water use.

Studies and projections of ecosystem responses to drought remain underrepresented in the literature. Furthermore, dry sites (such as those in Australia) have been shown to be more vulnerable to global changes because they are already operating under water-stressed conditions which are also often hot and dry. Further research in Australian ecosystems will provide more robust projections of climate change impacts on transpiration.

Responses of transpiration at leaf and canopy scales to CO_2 enrichment, temperature increases and rainfall declines and combined effects of climate change in Australia.

	CO_2 enrichment	Temperature increase	Rainfall decline	Combined effects of climate change
Leaf-scale transpiration	Reduced stomatal conductance	Increased stomatal conductance but will cause reductions over a threshold temperature	Reduced soil moisture which reduces stomatal conductance	Reduced stomatal conductance overall
Canopy-scale transpiration with increased leaf area	May be no change due to larger leaf area	May be little change due to self-shading	Reduced canopy conductance due to limited soil moisture	Decreased transpiration
Canopy-scale transpiration with no increased leaf area	Reduced transpiration	Increased transpiration	Reduced transpiration	Decreased transpiration

Responses of landscape water balances to climate change

Estimating the impact of climate change on water balances (especially run-off for human consumption) is a complicated process. It involves considering the range of climate change scenarios (including changes in total rainfall over the year as well as seasonality of rainfall), determining the range of responses of vegetation and incorporating these data into hydrological models. Most hydrological models can be simplified to,

$$Q = P - ET$$

Where Q is the run-off or water yield, P is the incoming precipitation and ET is evapotranspiration (of which transpiration generally makes up 70 to 95%). Streamflow, soil moisture store and groundwater recharge are all components of Q. In combination with a reduction in rainfall, declining transpiration will impact on the hydrological cycle by changing the proportions of water available for river flow, ground water recharge and human consumption (all components of Q). When water is scarce, a greater proportion of rainfall is used in transpiration than when rainfall is abundant. For example, during a dry year, 98% of rainfall was used by vegetation in a remnant woodland but in a wet year, that dropped to 89%. Consequently catchment yield will decline under climate change conditions of reduced rainfall and increased evaporative demand

Decreases in rainfall and higher rates of evapotranspiration (as a proportion of rainfall) in response to climate change are predicted to cause a decrease in run-off by 10 to 30% by 2050 in Australia. This will place further stress on Australia's limited water supply. Similarly, a recent study of catchments in Victoria found that run-off would decline by up to 45% under the driest climate change scenarios by 2030 and this would get much worse by 2070. Estimates for NSW and ACT are less clear-cut, with changes in mean annual run-off projected to fall between the ranges of a decrease by 14% or an increase by 10% (depending on the climate change scenario). However, in the Murray-Darling catchment, run-off is expected to decline by 10-25% by 2050. In WA, significant reductions in streamflow have already been measured with declines in inflows to Perth's reservoirs occurring since 1974. Average water volumes for 1997 to 2004 were only one third of those for 1911 to 1974. In the Stirling catchment (WA), run-off is expected to decline by a further 31% by 2050. Comparing these numbers to the predicted rainfall declines for each area, there is a clear amplification of declines in run-off in comparison to rainfall declines. This is because run-off occurs only once the soil profile is saturated and with reductions in rainfall, the frequency with which the soil profile is saturated declines and therefore run-off declines more than the decline in rainfall.

These values based on hydrological models depend on the model used, the calibration method and the climate change scenario applied in the model. There is another approach which is independent of hydrological and climate change models. The relationship between rainfall and run-off can be calculated as the rainfall elasticity of runoff (the proportional change in mean annual run-off divided by the proportional change in mean annual rainfall). This approach can be applied using historical data across large areas where appropriate data for complex hydrological models are not available. If the elasticity value is 2-3, a 10% decline in rainfall will cause a 20-30% reduction in run-off. This relationship is greater in drier regions so the proportional decline in run-off is greater where water is in limited supply. Many coastal areas of eastern Australia have values between 2 and 2.5. For inland NSW, Vic and in the NT and WA, values are greater than 3. These findings confirm the outputs of the hydrological models detailed above.

Due to increasing occurrence of extreme weather conditions, there may be an increase in large run-off events which is often omitted from hydrological models using annual timesteps. The result is that the calculated reduction in mean annual run-off may be slightly overestimated. However, if the water from these extreme run-off events cannot be harvested and effectively stored it may not make a significant impact on the available water supply of an area.

Human activities and natural variability are already impacting on water supply in Australia as evidenced by recent wide-spread and sustained droughts. Since 2002, most land in the eastern states and south-west region of the continent have been in drought conditions comparable to the worst droughts on record. The area impacted by droughts is predicted to increase under climate change with obvious impacts on water supply.

Added environmental stressors which exacerbate limited water availability include land clearing, dryland salinity, over-allocation and inefficient use of water resources, fragmentation of ecosystems and intensification of agriculture. Under climate change conditions, water inputs will be more scarce and outputs will multiply (through enhanced evapotranspiration in many areas), placing added pressure on water supplies and drastically altering landscape water balances. Water availability is projected to be one of the most pressing issues under projected climate change scenarios.

Implications for stream flow, groundwater recharge and irrigation

With declining precipitation across much of the most densely inhabited parts of the continent, there will be less water available for all components of the hydrological cycle. Furthermore, water yield will decline as a larger proportion of precipitation is used as evapotranspiration, leaving less water for streamflow, groundwater recharge and irrigation.

Any reduction in run-off will severely compromise water quality. Rivers already under stress from salinisation and over allocation and declining flows will be further damaged by reduced streamflow. Higher temperatures and still water stimulate algal blooms, causing other imbalances in water chemistry. Aquatic and riparian ecosystems will be further degraded and water will be unfit for human use. Increased frequency of fires, storms and droughts under climate change conditions will exacerbate erosion and sedimentation of rivers.

Little is known about the impact of climate change on groundwater recharge in Australia according to a recent Intergovernmental Panel on Climate Change technical paper. However, it is likely that reduced water yields in catchments will cause declines in groundwater recharge. Reductions in groundwater recharge will impact on Australia's water supplies in aquifers. Many inland areas rely on groundwater for agriculture, industry and domestic use. For instance, the Great Artesian Basin is a confined aquifer underlying approximately one fifth of the continent, supplying the only reliable water source across its area. Before European settlement, inflows were in equilibrium with outflows through springs and baseflow of rivers. The use of bores to access water in the aquifer greatly increased the volume of water reaching the surface, depleting water reserves. With plugging of disused bores and more efficient use of water, this resource is now being used more carefully. However, a reduction of recharge due to climate change will lead to further imbalance and sustainable management of this resource in the future will require reductions in the volume of water extracted from bores, impacting on agricultural and industrial activities. This is true throughout the continent as groundwater levels and flows decline.

Agriculture is by far the largest water consuming activity in Australia and irrigation is the major water usage. Approximately 75% of irrigation water comes from the Murray-Darling so significantly reduced water levels under climate change in this system will impact on water available for irrigation. Lower soil moisture, higher evaporative demand, increased frequency and intensity of droughts and reductions in rainfall (leading to decreased run-off) will exacerbate water stress. Irrigation practices will need to be drastically altered to account for reduced supply and greater atmospheric demand.

Conclusions

Climate change will cause hotter, drier conditions with less rainfall across the majority of the Australian continent. While most ecosystems are already well adapted to water-limitation, the further reduction of water availability coupled with increased atmospheric water demands will have a significant impact on vegetation water use. Transpiration will decline due to reduced rainfall causing reduced soil moisture. Vegetation water use plays a major part in the hydrological cycle with between 70 and 95% of rainfall lost as evapotranspiration. As rainfall decreases, the proportion of rainfall used in evapotranspiration increases, reducing the water yield available for human consumption. Reduction in available water supplies also threatens the quality of water through changes in water chemistry. Current practices in water use are not sustainable and more water efficient practices need to be developed to avoid a water crisis.

References and further reading

CSIRO (2007). *Climate change in Australia - Technical Report*. CSIOR and BoM, Canberra. http://www.climatechangeinaustralia.gov.au/resources.php

Eamus, D. Hatton, T. Cook, P. Colvin, C. (2006). *Ecohydrology: Vegetation function, water and resource management*. CSIRO Publishing, Collingwood, Victoria.

Foran, B. and Poldy, F. (2002). *Future dilemmas. Options to 2050 for Australia's population, technology, resources and environment*. Working paper 02/01. CSIRO Sustainable Ecosystems, Canberra.

Garnaut, R. (2008) *The Garnaut Climate Change Review: Final Report*. Cambridge University Press, Port Melbourne. Available online at: http://www.garnautreview.org.au/

IPCC (2007) *Fourth Assessment Report. Working group 1 report "The Physical Science Basis"* http://www.ipcc.ch/ipccreports/ar4- wg1.htm

IPCC (2008) *Technical Paper VI: Climate Change and Water*. http://www.ipcc.ch/pdf/technicalpapers/ climate-change-water-en.pdf

Van Dijk, A. Evans, R. Hairsine, P. Khan, S. Nathan, R. Paydar, Z. Viney, N, Zhang, L. (2006) *Risks to the shared water resources of the Murray-Darling Basin*. Murray-Darling Basin Commission, Canberra.