

Developed at the request of:



Research conducted by:



Climate: Observations, projections and impacts: Australia

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The country reports were written by a range of climate researchers, chosen for their subject expertise, who were drawn from institutes across the UK. Authors from the Met Office and the University of Nottingham collated the contributions in to a coherent narrative which was then reviewed. The authors and contributors of the reports are as above.

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Climate: Observations, projections and impacts



We have reached a critical year in our response to climate change. The decisions that we made in Cancún put the UNFCCC process back on track, saw us agree to limit temperature rise to 2 °C and set us in the right direction for reaching a climate change deal to achieve this. However, we still have considerable work to do and I believe that key economies and major emitters have a leadership role in ensuring a successful outcome in Durban and beyond.

To help us articulate a meaningful response to climate change, I believe that it is important to have a robust scientific assessment of the likely impacts on individual countries across the globe. This report demonstrates that the risks of a changing climate are wide-ranging and that no country will be left untouched by climate change.

I thank the UK's Met Office Hadley Centre for their hard work in putting together such a comprehensive piece of work. I also thank the scientists and officials from the countries included in this project for their interest and valuable advice in putting it together. I hope this report will inform this key debate on one of the greatest threats to humanity.

The Rt Hon. Chris Huhne MP, Secretary of State for Energy and Climate Change



There is already strong scientific evidence that the climate has changed and will continue to change in future in response to human activities. Across the world, this is already being felt as changes to the local weather that people experience every day.

Our ability to provide useful information to help everyone understand how their environment has changed, and plan for future, is improving all the time. But there is still a long way to go. These reports – led by the Met Office Hadley Centre in collaboration with many institutes and scientists around the world – aim to provide useful, up to date and impartial information, based on the best climate science now available. This new scientific material will also contribute to the next assessment from the Intergovernmental Panel on Climate Change.

However, we must also remember that while we can provide a lot of useful information, a great many uncertainties remain. That's why I have put in place a long-term strategy at the Met Office to work ever more closely with scientists across the world. Together, we'll look for ways to combine more and better observations of the real world with improved computer models of the weather and climate; which, over time, will lead to even more detailed and confident advice being issued.

Julia Slingo, Met Office Chief Scientist

Introduction

Understanding the potential impacts of climate change is essential for informing both adaptation strategies and actions to avoid dangerous levels of climate change. A range of valuable national studies have been carried out and published, and the Intergovernmental Panel on Climate Change (IPCC) has collated and reported impacts at the global and regional scales. But assessing the impacts is scientifically challenging and has, until now, been fragmented. To date, only a limited amount of information about past climate change and its future impacts has been available at national level, while approaches to the science itself have varied between countries.

In April 2011, the Met Office Hadley Centre was asked by the United Kingdom's Secretary of State for Energy and Climate Change to compile scientifically robust and impartial information on the physical impacts of climate change for more than 20 countries. This was done using a consistent set of scenarios and as a pilot to a more comprehensive study of climate impacts. A report on the observations, projections and impacts of climate change has been prepared for each country. These provide up to date science on how the climate has already changed and the potential consequences of future changes. These reports complement those published by the IPCC as well as the more detailed climate change and impact studies published nationally.

Each report contains:

- A description of key features of national weather and climate, including an analysis of new data on extreme events.
- An assessment of the extent to which increases in greenhouse gases and aerosols in the atmosphere have altered the probability of particular seasonal temperatures compared to pre-industrial times, using a technique called 'fraction of attributable risk.'
- A prediction of future climate conditions, based on the climate model projections used in the Fourth Assessment Report from the IPCC.
- The potential impacts of climate change, based on results from the UK's Avoiding Dangerous Climate Change programme (AVOID) and supporting literature.
For details visit: <http://www.avoid.uk.net>

The assessment of impacts at the national level, both for the AVOID programme results and the cited supporting literature, were mostly based on global studies. This was to ensure consistency, whilst recognising that this might not always provide enough focus on impacts of most relevance to a particular country. Although time available for the project was short, generally all the material available to the researchers in the project was used, unless there were good scientific reasons for not doing so. For example, some impacts areas were omitted, such as many of those associated with human health. In this case, these impacts are strongly dependant on local factors and do not easily lend themselves to the globally consistent framework used. No attempt was made to include the effect of future adaptation actions in the assessment of potential impacts. Typically, some, but not all, of the impacts are avoided by limiting global average warming to no more than 2 °C.

The Met Office Hadley Centre gratefully acknowledges the input that organisations and individuals from these countries have contributed to this study. Many nations contributed references to the literature analysis component of the project and helped to review earlier versions of these reports.

We welcome feedback and expect these reports to evolve over time. For the latest version of this report, details of how to reference it, and to provide feedback to the project team, please see the website at www.metoffice.gov.uk/climate-change/policy-relevant/obs-projections-impacts

In the longer term, we would welcome the opportunity to explore with other countries and organisations options for taking forward assessments of national level climate change impacts through international cooperation.

Summary

Climate observations

- There has been a reduction in the frequency of cool nights and cool days and an increase in the frequency of warm nights and hot days over Australia with the changes most pronounced to the East of the country.
- There has been a general increase in summer mean temperatures averaged over the country as a result of human influence on climate, making the occurrence of warm summer temperatures more frequent and cold summer temperatures less frequent.

Climate change projections

- For the A1B emissions scenario projected temperature increases are larger over central and western regions of Australia, with changes of up to around 4°C. Along most of the coastal regions, changes of around 2.5°C are more typical. There is good agreement between the CMIP3 models over all of Australia.
- For precipitation changes, there is moderate to low agreement amongst the CMIP3 ensemble of models. Decreases of around 20% or more are projected over some parts of the far west, but moderate decreases of around 5% are more typical over most of Western Australia, as well as eastern Queensland, Victoria, and southern South Australia. Much of the Northern Territory, Queensland, and parts of New South Wales are projected to experience increases of up to 5%, with increases of up to 10% in the far north.

Climate change impacts projections

Crop yields

- A number of global- and regional-scale studies included here project yield increases in the near and medium future for wheat, one of the country's major crops, although this is not true for all studies.
- However, simulations by the AVOID programme indicate that, of the land currently cultivated in Australia, much of it could become less suitable for agricultural production as a result of climate change.

- National-scale studies highlight sub-regional variation in the vulnerability of crop yields to climate change and moreover a need for implementation of adaptation strategies to cope with climate change, particularly for the rice and grape wine industries.

Food security

- Australia is currently a country with extremely low levels of undernourishment. Global-scale studies included here project that the country as a whole may remain food secure over the next 40 years, partly due to the country's strong purchasing power and adaptive capacity.

Water stress and drought

- The global and regional assessments show a high degree of uncertainty regarding how water availability in Australia could be affected by climate change.
- However, there is some consensus that south-eastern Australia could become drier with climate change, which could increase water stress in this region. This could be exacerbated by increasing population pressures.
- Recent simulations by the AVOID programme do not project an increase or decrease in the exposure of Australia's population to water stress with climate change.

Pluvial flooding and rainfall

- The CMIP3 projected a tendency for reducing rainfall over many regions of Australia but also that that extremes may increase.
- More recent research generally agrees with this, but has highlighted differences and uncertainties in changes at the regional level. This is in part due to incomplete an understanding of how climate change will influence large-scale systems such as the El-Nino Southern Oscillation, the large-scale monsoon system, and changes to tropical cyclones.

Fluvial Flooding

- Floods in Queensland and New South Wales in December 2010 were the most significant in Australia since at least the 1970s in terms of extent and impact.
- However, there is large uncertainty in projections of fluvial flooding for Australia under climate change.

- Recent simulations by the AVOID programme confirm this uncertainty. A majority of the simulations showing a decreasing trend in flood risk by the 2030s, but with increasing uncertainty in projections through the century.

Tropical cyclones

- There remains large uncertainty in the current understanding of how tropical cyclones might be affected by climate change. Caution should be applied in interpreting model-based results, even where the models are in agreement.
- A review of the current literature suggests that the frequency of tropical cyclones in the Southwest Pacific and South Indian Ocean basins could decrease in a warmer world, reducing the overall probability of tropical cyclone landfall on Australia's east and west coasts, respectively.
- However, a southward shift in tropical cyclone tracks has been reported by several studies, which may increase the risk of damage from landfalling cyclones near Australia's more heavily populated cities.
- A number of recent studies included here suggest that tropical cyclone intensities may increase with climate change, which could place vulnerable communities in the Torres Strait Islands at risk.

Coastal regions

- Australia is characterised by densely and increasingly populated coastal areas; 80% of the population live within 50 km of the coast.
- Several studies suggest that Sea Level Rise (SLR) could increase coastal flooding in Australia. However, the absolute magnitude of the simulated impacts tend to be relatively small when compared with other countries across the globe.

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Chapter 1- Climate Observations

Rationale

Present day weather and climate play a fundamental role in the day to day running of society. Seasonal phenomena may be advantageous and depended upon for sectors such as farming or tourism. Other events, especially extreme ones, can sometimes have serious negative impacts posing risks to life and infrastructure and significant cost to the economy. Understanding the frequency and magnitude of these phenomena, when they pose risks or when they can be advantageous and for which sectors of society, can significantly improve societal resilience.

In a changing climate it is highly valuable to understand possible future changes in both potentially hazardous events and those reoccurring seasonal events that are depended upon by sectors such as agriculture and tourism. However, in order to put potential future changes in context, the present day must first be well understood both in terms of common seasonal phenomena and extremes.

The purpose of this chapter is to summarise the weather and climate from 1960 to present day. This begins with a general climate overview including an up to date analysis of changes in surface mean temperature. These changes may be the result of a number of factors including climate change, natural variability and changes in land use. There is then a focus on extremes of temperature, precipitation and storms selected from 1996 onwards, reported in the World Meteorological Organization (WMO) Annual Statements on the Status of the Global Climate and/or the Bulletin of the American Meteorological Society (BAMS) State of the Climate reports. This is followed by a discussion of changes in moderate extremes from 1960 onwards using an updated version of the HadEX extremes database (Alexander et al. 2006) which categorises extremes of temperature and precipitation. These are core climate variables which have received significant effort from the climate research community in terms of data acquisition and processing and for which it is possible to produce long high quality records for monitoring. No new analysis is included for storms (see the methodology annex for background). For seasonal temperature extremes, an attribution analysis then puts the seasons with highlighted extreme events into context of the recent climate versus a hypothetical climate in the absence of anthropogenic emissions (Christidis et al, 2011). It is important to note that we carry out our attribution analyses on seasonal mean temperatures

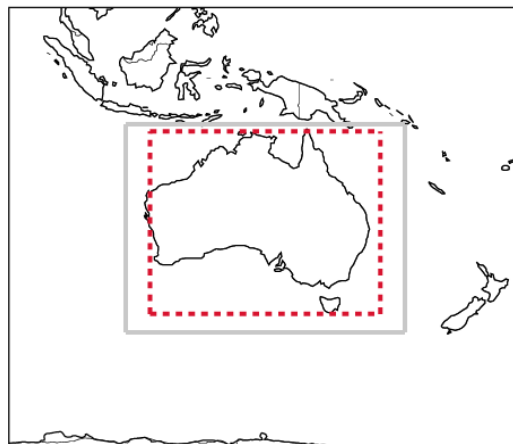


Figure 1. Location of boxes for the regional average time series (red dashed box) in Figures 3 and 5 and the attribution region (grey box) in Figure 4.

over the entire country. Therefore these analyses do not attempt to attribute the changed likelihood of individual extreme events. The relationship between extreme events and the large scale mean temperature is likely to be complex, potentially being influenced by *inter alia* circulation changes, a greater expression of natural internal variability at smaller scales, and local processes and feedbacks. Attribution of individual extreme events is an area of developing science. The work presented here is the foundation of future plans to systematically address the region's present and projected future weather and climate, and the associated impacts.

The methodology annex provides details of the data shown here and of the scientific analyses underlying the discussions of changes in the mean temperature and in temperature and precipitation extremes. It also explains the methods used to attribute the likelihood of occurrence of seasonal mean temperatures.

Climate overview

Much of Australia is warm or hot throughout the year and even along the cooler southern coasts the winters are mild rather than cold. Very high temperatures with low humidity occasionally occur almost anywhere in Australia when winds blow out from the interior. Tasmania is an exception in having a temperate climate, with an annual mean temperature of 13°C at Hobart. Melbourne, on the south coast has an annual mean temperature of 15°C, and Perth, on the South West coast, 18°C. Brisbane on the east coast and central Alice Springs both have annual mean temperatures of 21°C, but Alice Springs has a continental climate with much greater seasonal variability and diurnal range. In the tropical north, Darwin is hot throughout the year with a mean temperature of 28°C, and the weather can be very sultry and oppressive in summer.

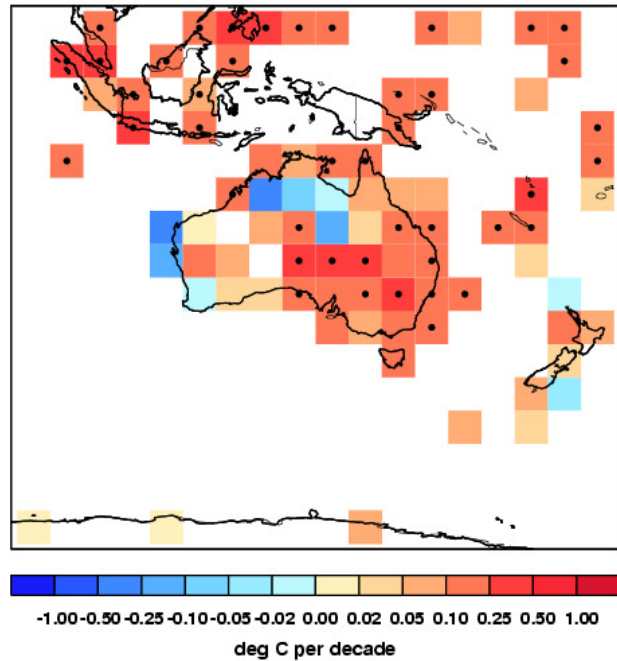
Australia has latitudes ranging from 10 to 43°S, so it has a wide range of climates. Spanning the circum-global belt of high pressure around 30-35°S, there is a large area of desert in central southern Australia with annual mean rainfall less than 200 mm. In south-eastern Australia there is a good distribution of rainfall throughout the year, for example at Melbourne which has 650 mm annually with very little seasonal variability. Perth, however, has a winter maximum of rainfall, with an annual average of 800 mm, most of which falls from May to September. Tasmania is a mountainous island which is exposed to the stormy westerly winds which bring heavy rain up to 2500 mm per year in places, although Hobart is more sheltered and has only 570 mm spread through the year. In the north and north-east there is a tropical region with dry winters and very wet summers caused by the seasonal monsoon associated with the annual oscillation of the inter-tropical convergence zone (ITCZ). Darwin has annual average rainfall of 1700 mm and Cairns, on the north-east coast, 2000 mm.

A strong warm phase of the El Niño Southern Oscillation (ENSO) can lead to extended drought periods in north and north-eastern Australia. Heat waves also occur in southern Australia, and serious bush fires can be caused by prolonged heat waves and droughts. Tropical cyclones occur two or three times a year in the seas to the north-east and north-west of Australia. The northern part of the Queensland coast and the coast from Darwin southwards are affected by the torrential rain and sometimes very high winds near the storm centres.

Analysis of long-term features in the mean temperature

CRUTEM3 data (Brohan et al., 2006) have been used to provide an analysis of mean temperatures from 1960 to 2010 over Australia using the median of pairwise slopes method to fit the trend (Sen, 1968; Lanzante, 1996). The methods are fully described in the methodology annex. In agreement with increasing global average temperatures (Sánchez-Lugo et al. 2011), there is a widespread warming signal for temperature over Australia, especially in the east, as shown in Figure 2. During the winter (June to August) the warming is more spatially consistent, with higher confidence that the trend is different from zero in a large proportion of grid-boxes showing warming, especially in the eastern half of the country. For summer (December to February) the signal is more mixed, particularly in the north and west regions where confidence in the signal is low. Similar to winter, the eastern and southern regions show a coherent warming pattern with high confidence for most of the grid boxes. Regionally averaged trends (over grid boxes included in the red dashed box in Figure 1) calculated by the median of pairwise slopes show clear warming trends with higher confidence. This trend for summer is 0.12 °C per decade (5th to 95th percentile of slopes: 0.04 to 0.21 °C per decade) and for winter is 0.17 °C per decade (5th to 95th percentile of slopes: 0.07 to 0.26 °C per decade).

DJF



JJA

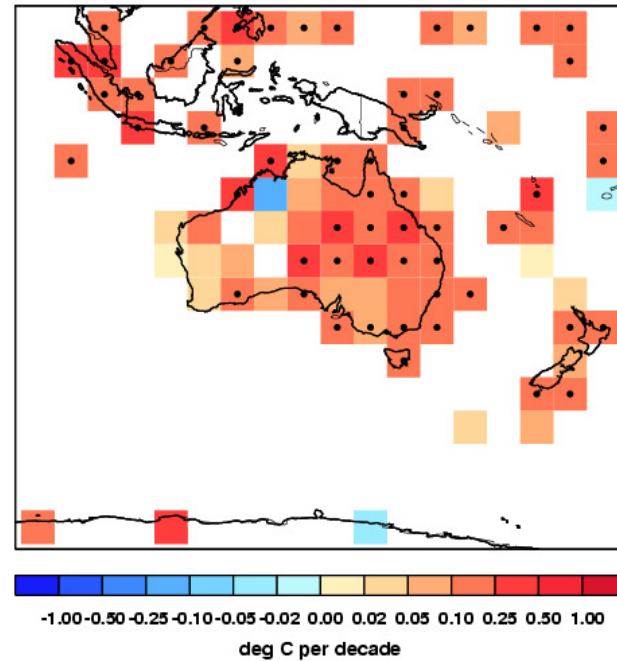


Figure 2. Decadal trends in seasonally averaged temperatures for Australia and the surrounding regions over the period 1960 to 2010. Monthly mean anomalies from CRUTEM3 (Brohan et al. 2006) are averaged over each 3 month season (December-January-February – DJF and June-July-August – JJA). Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). There is high confidence in the trends shown if the 5th to 95th percentiles of the pairwise slopes do not encompass zero because here the trend is considered to be significantly different from a zero trend (no change). This is shown by a black dot in the centre of the respective grid-box.

Temperature extremes

Both hot and cold temperature extremes can place many demands on society. While seasonal changes in temperature are normal and indeed important for a number of societal sectors (e.g. tourism, farming etc.), extreme heat or cold can have serious negative impacts. Importantly, what is 'normal' for one region may be extreme for another region that is less well adapted to such temperatures.

Parts of the Australian continent can receive high variations in temperature between seasons and also on an interannual basis.. High temperatures, particularly in summer, have exacerbated the impact of droughts, and also affected rainfall, evaporation, runoff, and more generally water resources for human use. 2009 was Australia's second warmest year on record and the last decade has been the warmest on record (UNFCC, 2010).

Table 1 shows selected extreme events since 1996 that are reported in World Meteorological Organization (WMO) Statements on Status of the Global Climate and/or Bulletin of the American Meteorological Society (BAMS) State of the Climate reports. The heat wave which affected south eastern Australia in early 2009 is highlighted below as an example of an extreme temperature event for the region.

Year	Month	Event	Details	Source
2003	Sept	Heat wave	Record maximum September temperatures set in many places including a new Australian September record daily maximum of 43.1°C set in West Roebuck.	WMO (2004); Levinson and Wapple, (2004)
2004	Feb	Heat wave	Intense and widespread, many city records broken.	WMO (2005)
2009	Jan/Feb	Heat wave	Record breaking heat wave, with associated dry conditions and bush-fires.	WMO (2010); Blunden et al. (2010)

Table 1: selected extreme temperature events reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 1996.

Recent extreme temperature events

Heat wave, January-Feb 2009

In early 2009 a slow moving high-pressure system settled over the Tasman Sea, which together with an intense tropical low located off the North West Australian coast and a monsoon trough over Northern Australia created ideal conditions for hot tropical air to be directed over south eastern Australia (National Climate Centre, BoM, 2009). The resulting heat wave brought record temperatures to the region. The highest temperature recorded during the heat wave was 48.8 °C in Hopetoun, Victoria, a record for the state (National Climate Centre, BoM, 2009). Adelaide reached its third-highest temperature, 45.7 °C, and Melbourne recorded its highest ever temperature on record, 46.4 °C. Both cities broke records for the most consecutive days over 40 °C, while Mildura, Victoria recorded an all time record twelve consecutive days over 40 °C. The media reported power outages and disruption to rail services resulting from infrastructure damage from the extreme heat (ABC News, 2009, Houston, Cameron; Reilly, Tom, 2009). An estimated 347 people died as a result of the heat-wave (EM-DAT).

The 2009 heat-wave created excellent conditions for bushfires. The 'Black Saturday bushfires', as they became known, claimed 173 lives and destroyed 2,133 houses (Victorian Bushfires Royal Commission, 2010).

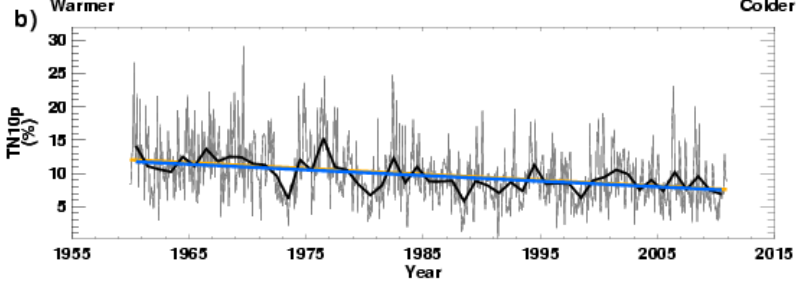
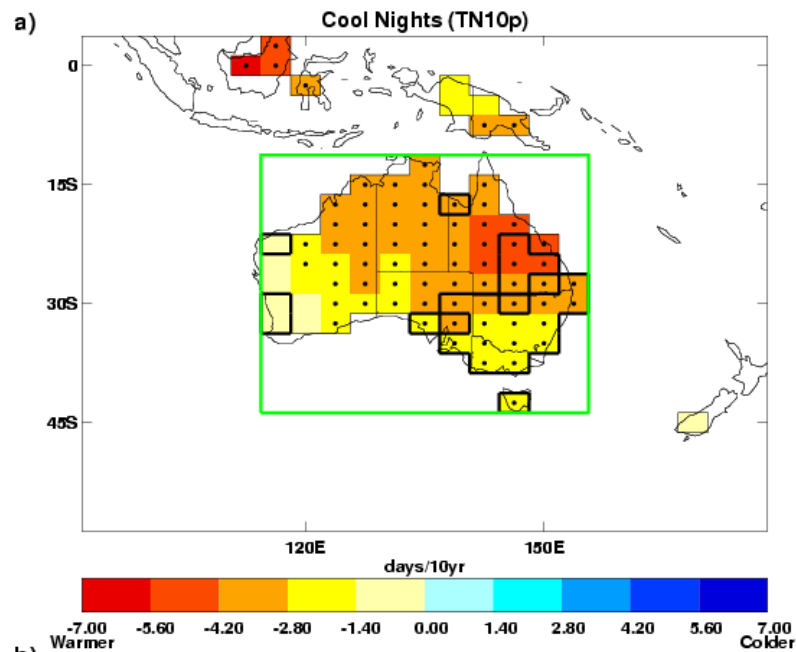
Analysis of long-term features in moderate temperature extremes

GHCND data (Durre et al. 2010) have been used to update the HadEX extremes analysis for Australia from 1960 to 2010 using daily maximum and minimum temperatures. Here we discuss changes in the frequency of cool days and nights and warm days and nights which are moderate extremes. Cool days/nights are defined as being below the 10th percentile of daily maximum/minimum temperature and warm days/nights are defined as being above the 90th percentile of the daily maximum/minimum temperature. The methods are fully described in the methodology annex.

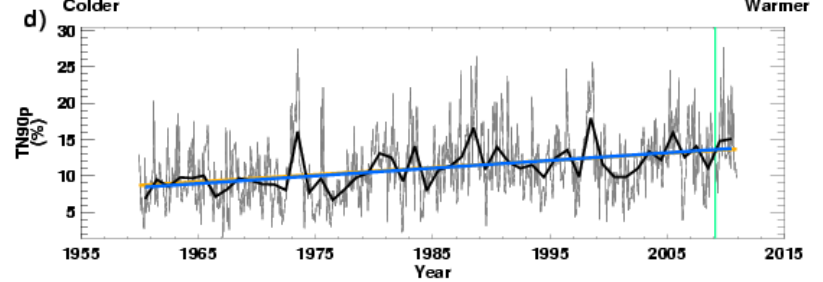
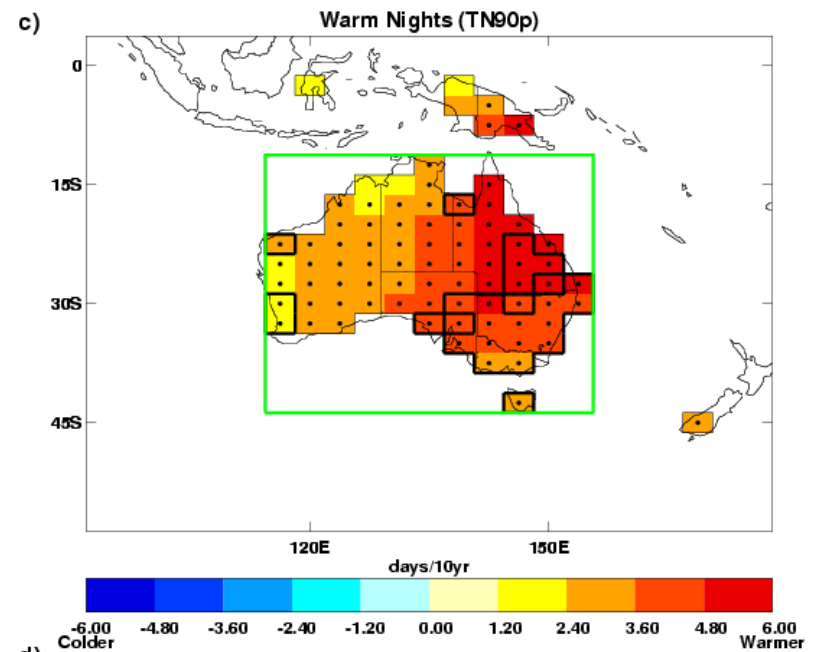
As shown in Figure 3 the number of cool nights has decreased most in Queensland, but all areas apart from the far west have higher confidence in a decrease. There appears to be a north-east to south-west gradient in the strength of the decline. The variation in the trend of the number of warm nights, however, has more of an east-west variation, with the strongest increase in the east of the country where higher confidence is a clear trend in all areas.

The interior of Australia has lower confidence in a trend of the number of cool days changing, with the coasts and eastern parts showing higher confidence. The strongest decline is seen in the south-eastern parts of the country. There is a strong signal which has higher confidence for an increase of the number of warm days throughout Australia, again with the eastern regions showing the strongest trend. Overall the signal for all four indices is strongest for the eastern parts of the country, with a weaker signal for the interior and west. This matches the behaviour observed for the mean temperatures indicating that it is likely that there has been a shift in the temperature distribution.

The time-series mirror the behaviour seen in the maps, with higher confidence that the trends are different from zero observed in all indices, both annually and monthly. The heat wave of 2009, although indicated on the time-series, is not clearly picked out in the curves. This is likely to have resulted from the fact that the heat wave was concentrated in the south-east of the country, and the signal will have been diluted by including all of Australia when creating the regional average.



Monthly: -0.88% per decade (-1.10 to -0.65)
 Total change of -4.38% from 1960 to 2010 (-5.51% to -3.26%)
 Annual: -0.84% per decade (-1.16 to -0.55)
 Total change of -4.22% from 1960 to 2010 (-5.80% to -2.74%)



Monthly: 0.98% per decade (0.75 to 1.22)
 Total change of 4.89% from 1960 to 2010 (3.77% to 6.08%)
 Annual: 1.06% per decade (0.67 to 1.46)
 Total change of 5.29% from 1960 to 2010 (3.33% to 7.29%)

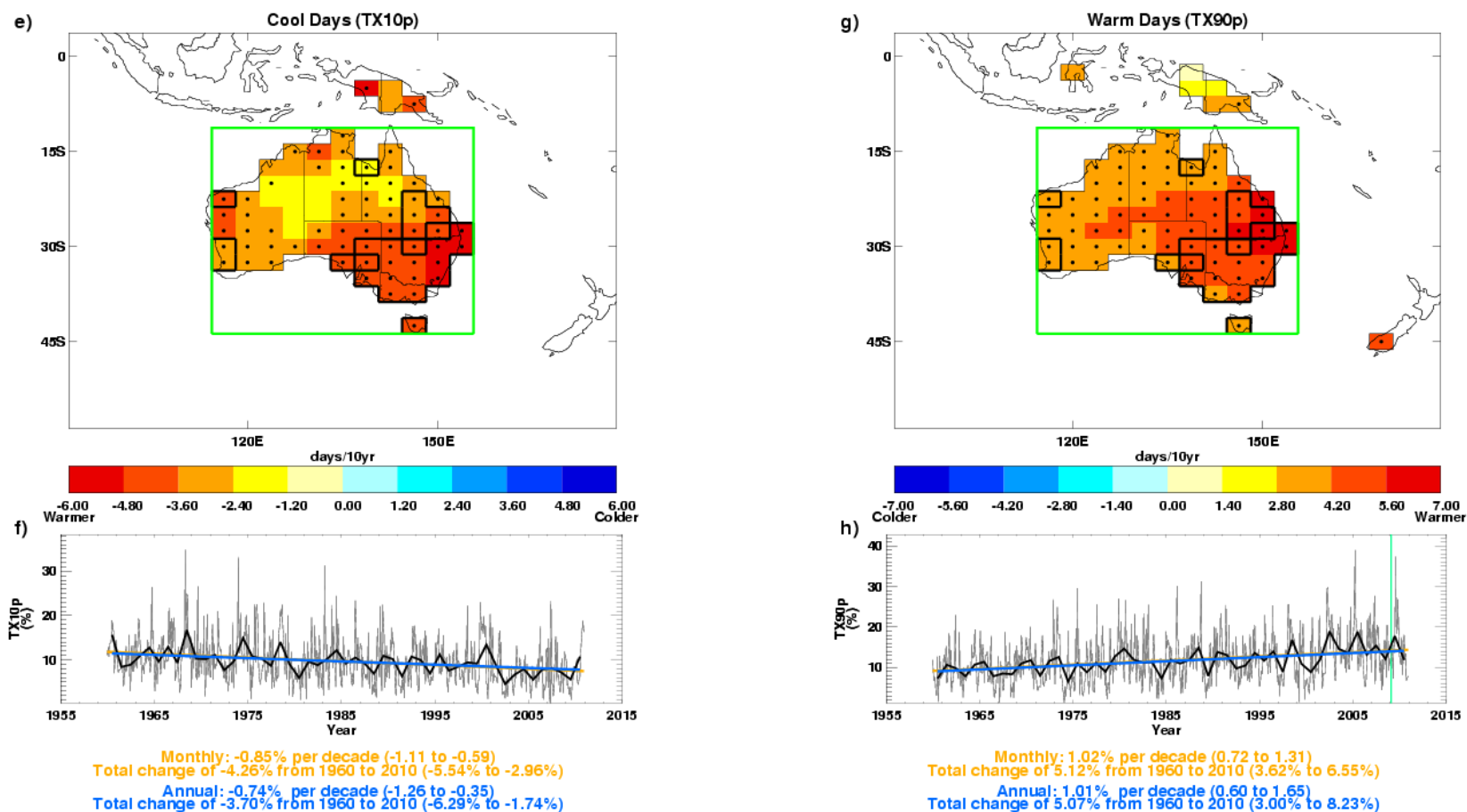


Figure 3. Change in cool nights (a,b), warm nights (c,d), cool days (e,f) and warm days (g,h) for Australia over the period 1960 to 2010 relative to 1961-1990 from the GHCND dataset (Durre et al., 2010). a,c,e,g) Grid-box decadal trends. Grid boxes outlined in solid black contain at least 3 stations and so are likely to be more representative of the wider grid box. Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). Higher confidence in a long-term trend is shown by a black dot if the 5th to 95th percentile slopes are of the same sign. Differences in spatial coverage occur because each index has its own decorrelation length scale (see the methodology annex). b,d,f,h) Area averaged annual time series for 114.375° to 155.625° E and 11.25° to 43.75° S as shown by the green box on the map and red box in Figure 1. Thin and thick black lines show the monthly and annual variation respectively. Monthly (orange) and annual (blue) trends are fitted as described above. The decadal trend and its 5th to 95th percentile confidence intervals are stated along with the change over the period for which data are available. All the trends have higher confidence that they are different from zero as their 5th to 95th percentile slopes are of the same sign. The green vertical lines show the dates of the heat wave in 2009.

Attribution of changes in likelihood of occurrence of seasonal mean temperatures

Today's climate covers a range of likely extremes. Recent research has shown that the temperature distribution of seasonal means would likely be different in the absence of anthropogenic emissions (Christidis et al., 2011). Here we discuss the seasonal means, within which the highlighted extreme temperature events occur, in the context of recent climate and the influence of anthropogenic emissions on that climate. The methods are fully described in the methodology annex.

Summer 2008/09

The distributions of the summer mean regional temperature in recent years in the presence and absence of anthropogenic forcings are shown in Figure 4. Analyses with both models suggest that human influences on the climate have shifted the distribution to higher temperatures. Considering the average over the entire region, the 2008/09 summer is not warm, as it lies near the cold tail of the temperature distributions for the climate influenced by anthropogenic forcings (distributions plotted in red). The season is further into the cold tail of the distribution estimated by the MIROC model, suggesting that it occurs less frequently than the HadGEM1 model indicates. In the absence of human influences on the climate (green distributions) both models suggest that the summer of 2008/09 would be average. The attribution results shown here refer to temperature anomalies over the entire region and over an entire season, and do not rule out the occurrence of a heat wave event that has a shorter duration and affects a smaller region.

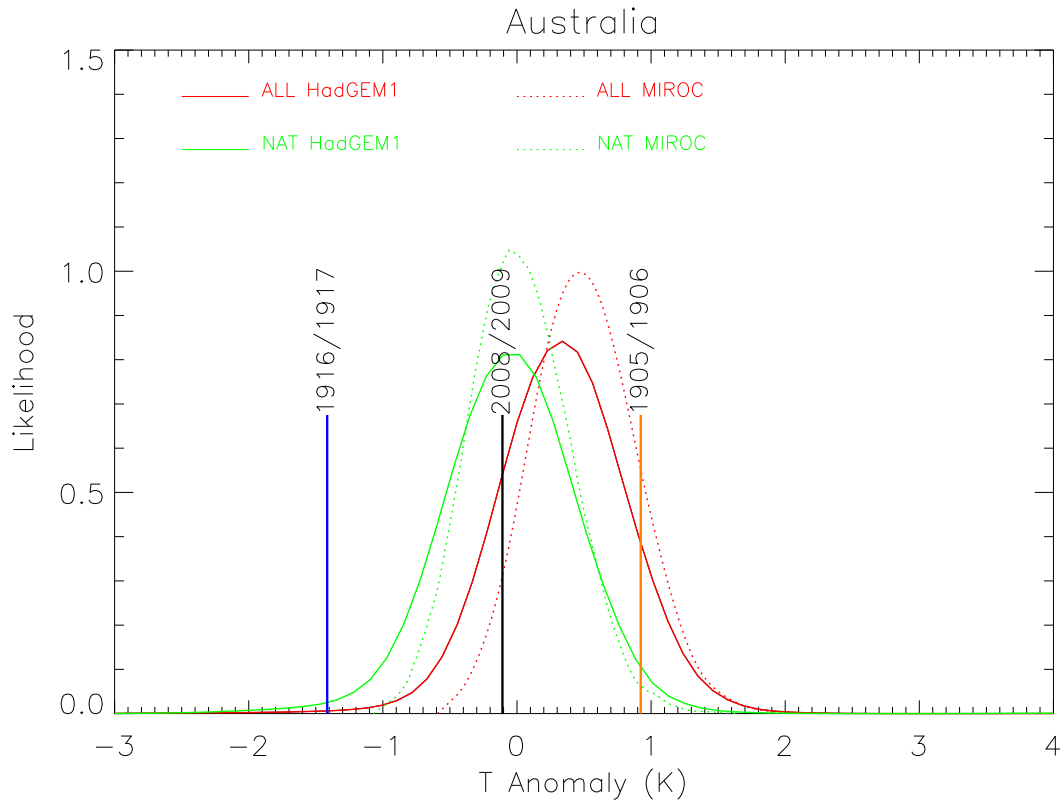


Figure 4. Distributions of the December-January-February mean temperature anomalies (relative to 1961-1990) averaged over the Australian region (110-160E, 47-10S – as shown in Figure 1) including (red lines) and excluding (green lines) the influence of anthropogenic forcings. The distributions describe the seasonal mean temperatures expected in recent years (2000-2009) and are based on analyses with the HadGEM1 (solid lines) and MIROC (dotted lines) models. The vertical black line marks the observed anomaly in summer 2008/09 and the vertical orange and blue lines correspond to the maximum and minimum anomaly in the CRUTEM3 dataset since 1900 respectively.

Precipitation extremes

Precipitation extremes, either excess or deficit, can be hazardous to human health, societal infrastructure, and livestock and agriculture. While seasonal fluctuations in precipitation are normal and indeed important for a number of societal sectors (e.g. tourism, farming etc.), flooding or drought can have serious negative impacts. These are complex phenomena and often the result of accumulated excesses or deficits or other compounding factors such as spring snow-melt, high tides/storm surges or changes in land use. The section deals purely with precipitation amounts.

Table 2 shows selected extreme precipitation events since 1996 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. The floods of 2010-11 are highlighted below as an example of an extreme precipitation event for Australia.

Year	Month	Event	Details	Source
1996-2009	-	Drought	Long term drought since 1996. Some regions experienced over a decade of drought.	WMO (2001); WMO (2010)
2000	Feb	Flooding	Flooding associated with Tropical Cyclone Steve affected northern and western areas of Australia.	WMO (2001); Lawrimore et al., (2001)
2003	Jan-Feb	Drought	Drought (SE Aus) and widespread bushfires.	WMO (2004); Levinson and Wapple, (2004)
2005	Jan-May	Drought	Exceptionally dry with 44% of the country experiencing rainfall in the bottom 10% of recorded totals.	WMO (2006)
2010-2011	Nov-Jan	Flooding	Widespread flooding in Queensland, New South Wales, northern and western Victoria and northern Tasmania.	National Climate Center, BoM (2011)

Table 2: Extreme precipitation events reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 1996.

Recent extreme precipitation events

Flooding, Nov 2010 - Jan 2011

Eastern Australia experienced a series of major rainfall events between November 2010 and January 2011, causing widespread flooding in Queensland, New South Wales, northern and western Victoria and northern Tasmania (National Climate Centre, BoM, 2011). These floods occurred during a strong La Niña event, during which sea surface temperatures were near record levels. Previous La Niña events have also been associated with severe flooding in eastern Australia. The floods of 2010/2011 were exacerbated by Tropical Cyclone Tasha, which made landfall south of Cairns on the morning of 25 December.

December 2010 set a new record area averaged rainfall across eastern Australia of 167.2 mm (132% above normal), with Queensland experiencing a record 209.5 mm on average (154% above normal) (National Climate Centre, BoM, 2011).

Analysis of long-term features in precipitation

HadEX extremes indices (Alexander et al. 2006) are used here for Australia from 1960 to 2003 using daily precipitation totals. Here we discuss changes in the annual total precipitation, and in the frequency of prolonged (greater than 6 days) wet and dry spells. The methods are fully described in the methodology annex.

The map of the change in total precipitation (Figure 5a) shows a low signal for the western parts of the country. The south eastern states show a strong decrease in the total precipitation, which has higher confidence than that for the rest of the country. The area around the Gulf of Carpentaria shows an increase in the total precipitation, but with lower confidence. These two signals, however, cancel out and the time series (Figure 5b) for the total precipitation shows no clear underlying trend. The flooding of November 2010 - January 2011 appears to have occurred after a wet year in 2009 which would have compounded the problem. However, the difference in the change of the total precipitation between the north and south of the country makes the identification of a signal in the time-series difficult.

The coverage for the continuous dry and continuous wet days (Figure 5 c to f) is poorer, with only the south east showing a signal which has higher confidence (increase and decrease respectively). However there is a coherent variation in the number of consecutive dry days, with a decrease in the west and an increase in the eastern and central regions.

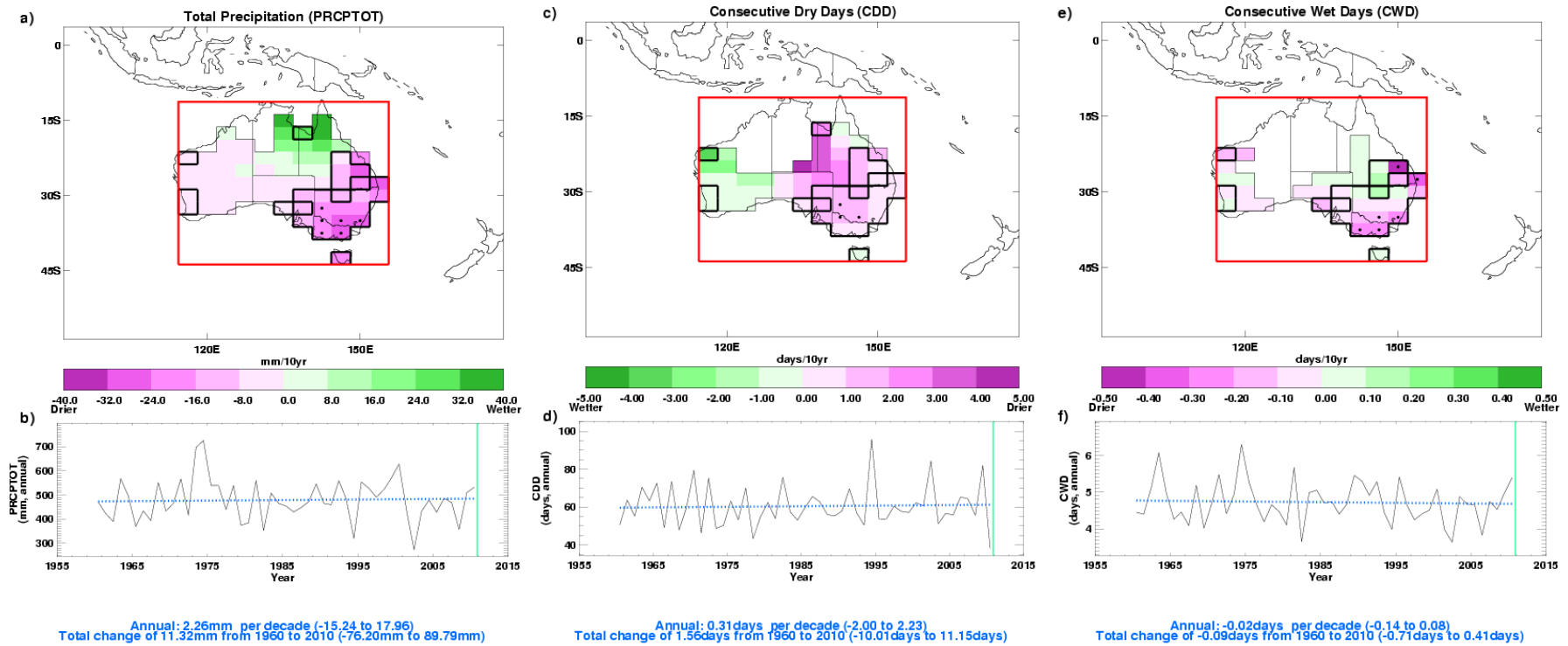


Figure 5. The change in annual total rainfall (a,b), the annual number of continuous dry days (c,d) and annual number of continuous wet days (e,f) over the period 1960-2010. The maps and timeseries have been created in exactly the same way as Figure 3. The vertical green lines show the date of the flooding of Nov 2010 – Jan2011. Only annual regional averages are shown in b,d,f). The dotted lines in b,d,f) indicate that there is lower confidence that the trends are different from zero.

Storms

Storms can be very hazardous to all sectors of society. They can be small with localised impacts or spread across large regions. There is no systematic observational analysis included for storms because, despite recent progress (Peterson et al. 2011; Cornes and Jones 2011), wind data are not yet adequate for worldwide robust analysis (see methodology annex). Further progress awaits studies of the more reliable barometric pressure data through the new 20th Century Reanalysis (Compo et al., 2011) and its planned successors.

Table 3 shows selected extreme events since 1996 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. Tropical Cyclone Larry is highlighted below as an example of a storm event affecting Australia.

Year	Month	Event	Details	Source
2006	March	Storm	Severe Tropical Cyclone Larry - high winds.	WMO (2007); Arguez (2007)

Table 3. Selected extreme temperature events reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 1996.

Recent storm events

Tropical cyclone Larry, 2006

Severe Tropical Cyclone Larry was among the most powerful tropical cyclones on record to make land fall in Australia, with winds of 185 km/h at landfall (WMO, 2007). It also caused extensive damage to crops, including the destruction of 80-90% of Australia's banana crop (BAMS, 2007).

Summary

The main features seen in observed climate over Australia are :

- There has been a reduction in the frequency of cool nights and cool days and an increase in the frequency of warm nights and hot days over Australia with the changes most pronounced to the East of the country.
- There has been a general increase in summer mean temperatures averaged over the country as a result of human influence on climate, making the occurrence of warm summer temperatures more frequent and cold summer temperatures less frequent.

Methodology annex

Recent, notable extremes

In order to identify what is meant by 'recent' events the authors have used the period since 1994, when WMO Status of the Global Climate statements were available to the authors. However, where possible, the most notable events during the last 10 years have been chosen as these are most widely reported in the media, remain closest to the forefront of the memory of the country affected, and provide an example likely to be most relevant to today's society. By 'notable' the authors mean any event which has had significant impact either in terms of cost to the economy, loss of life, or displacement and long term impact on the population. In most cases the events of largest impact on the population have been chosen, however this is not always the case.

Tables of recent, notable extreme events have been provided for each country. These have been compiled using data from the World Meteorological Organisation (WMO) Annual Statements on the Status of the Global Climate. This is a yearly report which includes contributions from all the member countries, and therefore represents a global overview of events that have had importance on a national scale. The report does not claim to capture all events of significance, and consistency across the years of records available is variable. However, this database provides a concise yet broad account of extreme events per country. This data is then supplemented with accounts from the monthly National Oceanic and Atmospheric Administration (NOAA) State of the Climate reports which outline global extreme events of meteorological significance.

We give detailed examples of heat, precipitation and storm extremes for each country where these have had significant impact. Where a country is primarily affected by precipitation or heat extremes this is where our focus has remained. An account of the impact on human life, property and the economy has been given, based largely on media reporting of events, and official reports from aid agencies, governments and meteorological organisations. Some data has also been acquired from the Centre for Research on Epidemiological Disasters (CRED) database on global extreme events. Although media reports are unlikely to be completely accurate, they do give an indication as to the perceived impact of an extreme event, and so are useful in highlighting the events which remain in the national psyche.

Our search for data has not been exhaustive given the number of countries and events included. Although there are a wide variety of sources available, for many events, an official

account is not available. Therefore figures given are illustrative of the magnitude of impact only (references are included for further information on sources). It is also apparent that the reporting of extreme events varies widely by region, and we have, where possible, engaged with local scientists to better understand the impact of such events.

The aim of the narrative for each country is to provide a picture of the social and economic vulnerability to the current climate. Examples given may illustrate the impact that any given extreme event may have and the recovery of a country from such an event. This will be important when considering the current trends in climate extremes, and also when examining projected trends in climate over the next century.

Observational record

In this section we outline the data sources which were incorporated into the analysis, the quality control procedure used, and the choices made in the data presentation. As this report is global in scope, including 23 countries, it is important to maintain consistency of methodological approach across the board. For this reason, although detailed datasets of extreme temperatures, precipitation and storm events exist for various countries, it was not possible to obtain and incorporate such a varied mix of data within the timeframe of this project. Attempts were made to obtain regional daily temperature and precipitation data from known contacts within various countries with which to update existing global extremes databases. No analysis of changes in storminess is included as there is no robust historical analysis of global land surface winds or storminess currently available.

Analysis of seasonal mean temperature

Mean temperatures analysed are obtained from the CRUTEM3 global land-based surface-temperature data-product (Brohan et al. 2006), jointly created by the Met Office Hadley Centre and Climatic Research Unit at the University of East Anglia. CRUTEM3 comprises of more than 4000 weather station records from around the world. These have been averaged together to create 5° by 5° gridded fields with no interpolation over grid boxes that do not contain stations. Seasonal averages were calculated for each grid box for the 1960 to 2010 period and linear trends fitted using the median of pairwise slopes (Sen 1968; Lanzante 1996). This method finds the slopes for all possible pairs of points in the data, and takes their median. This is a robust estimator of the slope which is not sensitive to outlying points. High confidence is assigned to any trend value for which the 5th to 95th percentiles of the pairwise slopes are of the same sign as the trend value and thus inconsistent with a zero trend.

Analysis of temperature and precipitation extremes using indices

In order to study extremes of climate a number of indices have been created to highlight different aspects of severe weather. The set of indices used are those from the World Climate Research Programme (WCRP) Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI). These 27 indices use daily rainfall and maximum and minimum temperature data to find the annual (and for a subset of the indices, monthly) values for, e.g., the ‘warm’ days where daily maximum temperature exceeds the 90th percentile maximum temperature as defined over a 1961 to 1990 base period. For a full list of the indices we refer to the website of the ETCCDI (<http://cccma.seos.uvic.ca/ETCCDI/index.shtml>).

Index	Description	Shortname	Notes
Cool night frequency	Daily minimum temperatures lower than the 10 th percentile daily minimum temperature using the base reference period 1961-1990	TN10p	---
Warm night frequency	Daily minimum temperatures higher than the 90 th percentile daily minimum temperature using the base reference period 1961-1990	TN90p	---
Cool day frequency	Daily maximum temperatures lower than the 10 th percentile daily maximum temperature using the base reference period 1961-1990	TX10p	---
Warm day frequency	Daily maximum temperatures higher than the 90 th percentile daily maximum temperature using the base reference period 1961-1990	TX90p	---
Dry spell duration	Maximum duration of continuous days within a year with rainfall <1mm	CDD	Lower data coverage due to the requirement for a ‘dry spell’ to be at least 6 days long resulting in intermittent temporal coverage
Wet spell duration	Maximum duration of continuous days with rainfall >1mm for a given year	CWD	Lower data coverage due to the requirement for a ‘wet spell’ to be at least 6 days long resulting in intermittent temporal coverage
Total annual precipitation	Total rainfall per year	PRCPTOT	---

Table 4. Description of ETCCDI indices used in this document.

A previous global study of the change in these indices, containing data from 1951-2003 can be found in Alexander et al. 2006, (HadEX; see <http://www.metoffice.gov.uk/hadobs/hadex/>).

In this work we aimed to update this analysis to the present day where possible, using the most recently available data. A subset of the indices is used here because they are most easily related to extreme climate events (Table 4).

Use of HadEX for analysis of extremes

The HadEX dataset comprises all 27 ETCCDI indices calculated from station data and then smoothed and gridded onto a $2.5^\circ \times 3.75^\circ$ grid, chosen to match the output from the Hadley Centre suite of climate models. To update the dataset to the present day, indices are calculated from the individual station data using the RClimDex/FClimDex software; developed and maintained on behalf of the ETCCDI by the Climate Research Branch of the Meteorological Service of Canada. Given the timeframe of this project it was not possible to obtain sufficient station data to create updated HadEX indices to present day for a number of countries: Brazil; Egypt; Indonesia; Japan (precipitation only); South Africa; Saudi Arabia; Peru; Turkey; and Kenya. Indices from the original HadEX data-product are used here to show changes in extremes of temperature and precipitation from 1960 to 2003. In some cases the data end prior to 2003. Table 5 summarises the data used for each country. Below, we give a short summary of the methods used to create the HadEX dataset (for a full description see Alexander et al. 2006).

To account for the uneven spatial coverage when creating the HadEX dataset, the indices for each station were gridded, and a land-sea mask from the HadCM3 model applied. The interpolation method used in the gridding process uses a decorrelation length scale (DLS) to determine which stations can influence the value of a given grid box. This DLS is calculated from the e-folding distance of the individual station correlations. The DLS is calculated separately for five latitude bands, and then linearly interpolated between the bands. There is a noticeable difference in spatial coverage between the indices due to these differences in decorrelation length scales. This means that there will be some grid-box data where in fact there are no stations underlying it. Here we apply black borders to grid-boxes where at least 3 stations are present to denote greater confidence in representation of the wider grid-box area there. The land-sea mask enables the dataset to be used directly for model comparison with output from HadCM3. It does mean, however, that some coastal regions and islands over which one may expect to find a grid-box are in fact empty because they have been treated as sea.

Data sources used for updates to the HadEX analysis of extremes

We use a number of different data sources to provide sufficient coverage to update as many countries as possible to present day. These are summarised in Table 5. In building the new

datasets we have tried to use exactly the same methodology as was used to create the original HadEX to retain consistency with a product that was created through substantial international effort and widely used, but there are some differences, which are described in the next section.

Wherever new data have been used, the geographical distributions of the trends were compared to those obtained from HadEX, using the same grid size, time span and fitting method. If the pattern of the trends in the temperature or precipitation indices did not match that from HadEX, we used the HadEX data despite its generally shorter time span. Differences in the patterns of the trends in the indices can arise because the individual stations used to create the gridded results are different from those in HadEX, and the quality control procedures used are also very likely to be different. Countries where we decided to use HadEX data despite the existence of more recent data are Egypt and Turkey.

GHCND:

The Global Historical Climate Network Daily data has near-global coverage. However, to ensure consistency with the HadEX database, the GHCND stations were compared to those stations in HadEX. We selected those stations which are within 1500m of the stations used in the HadEX database and have a high correlation with the HadEX stations. We only took the precipitation data if its $r > 0.9$ and the temperature data if one of its r -values > 0.9 . In addition, we required at least 5 years of data beyond 2000. These daily data were then converted to the indices using the *fclimdex* software.

ECA&D and SACA&D:

The European Climate Assessment and Dataset and the Southeast Asian Climate Assessment and Dataset data are pre-calculated indices comprising the core 27 indices from the ETCCDI as well as some extra ones. We kindly acknowledge the help of Albert Klein Tank, the KNMI¹ and the BMKG² for their assistance in obtaining these data.

Mexico:

The station data from Mexico has been kindly supplied by the SMN³ and Jorge Vazquez. These daily data were then converted to the required indices using the *Fclimdex* software. There are a total of 5298 Mexican stations in the database. In order to select those which

¹ Koninklijk Nederlands Meteorologisch Instituut – The Royal Netherlands Meteorological Institute

² Badan Meteorologi, Klimatologi dan Geofisika – The Indonesian Meteorological, Climatological and Geophysical Agency

³ Servicio Meteorológico Nacional de México – The Mexican National Meteorological Service

have sufficiently long data records and are likely to be the most reliable ones we performed a cross correlation between all stations. We selected those which had at least 20 years of data post 1960 and have a correlation with at least one other station with an r -value >0.95 . This resulted in 237 stations being selected for further processing and analysis.

Indian Gridded:

The India Meteorological Department provided daily gridded data (precipitation 1951-2007, temperature 1969-2009) on a $1^\circ \times 1^\circ$ grid. These are the only gridded daily data in our analysis. In order to process these in as similar a way as possible the values for each grid were assumed to be analogous to a station located at the centre of the grid. We keep these data separate from the rest of the study, which is particularly important when calculating the decorrelation length scale, which is on the whole larger for these gridded data.

Country	Region box (red dashed boxes in Fig. 1 and on each map at beginning of chapter)	Data source (T = temperature, P = precipitation)	Period of data coverage (T = temperature, P = precipitation)	Indices included (see Table 1 for details)	Temporal resolution available	Notes
Argentina	73.125 to 54.375 ° W, 21.25 to 56.25 ° S	Matilde Rusticucci (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	
Australia	114.375 to 155.625 ° E, 11.25 to 43.75 ° S	GHCND (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Land-sea mask has been adapted to include Tasmania and the area around Brisbane
Bangladesh	88.125 to 91.875 ° E, 21.25 to 26.25 ° N	Indian Gridded data (T,P)	1960-2007 (P), 1970-2009 (T)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Interpolated from Indian Gridded data
Brazil	73.125 to 31.875 ° W, 6.25 ° N to 33.75 ° S	HadEX (T,P)	1960-2000 (P) 2002 (T)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	Spatial coverage is poor
China	73.125 to 133.125 ° E, 21.25 to 53.75 ° N	GHCND (T,P)	1960-1997 (P) 1960-2003 (T _{min}) 1960-2010 (T _{max})	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Precipitation has very poor coverage beyond 1997 except in 2003-04, and no data at all in 2000-02, 2005-11
Egypt	24.375 to 35.625 ° E, 21.25 to 31.25 ° N	HadEX (T,P)	No data	TN10p, TN90p, TX10p, TX90p, PRCPTOT,	annual	There are no data for Egypt so all grid-box values have been interpolated from stations in Jordan, Israel, Libya and Sudan
France	5.625 ° W to 9.375 ° E, 41.25 to 51.25 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	

Germany	5.625 to 16.875 ° E, 46.25 to 56.25 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
India	69.375 to 99.375 ° E, 6.25 to 36.25 ° N	Indian Gridded data (T,P)	1960-2003 (P), 1970-2009 (T)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
Indonesia	95.625 to 140.625 ° E, 6.25 ° N to 11.25 ° S	HadEX (T,P)	1968-2003 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT,	annual	Spatial coverage is poor
Italy	5.625 to 16.875 ° E, 36.25 to 46.25 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Land-sea mask has been adapted to improve coverage of Italy
Japan	129.375 to 144.375 ° E, 31.25 to 46.25 ° N	HadEX (P) GHCND (T)	1960-2003 (P) 1960-2000 (T _{min}) 1960-2010 (T _{max})	TN10p, TN90p, TX10p, TX90p, PRCPTOT,	monthly, seasonal and annual (T), annual (P)	
Kenya	31.875 to 43.125 ° E, 6.25 ° N to 6.25 ° S	HadEX (T,P)	1960-1999 (P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT	annual	There are no temperature data for Kenya and so grid-box values have been interpolated from neighbouring Uganda and the United Republic of Tanzania. Regional averages include grid-boxes from outside Kenya that enable continuation to 2003
Mexico	118.125 to 88.125 ° W, 13.75 to 33.75 ° N	Raw station data from the Servicio Meteorológico Nacional (SMN) (T,P)	1960-2009 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	237/5298 stations selected. Non uniform spatial coverage. Drop in T and P coverage in 2009.
Peru	84.735 to 65.625 ° W, 1.25 ° N to 18.75 ° S	HadEX (T,P)	1960-2002 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	Intermittent coverage in TX90p, CDD and CWD

Russia	West Russia 28.125 to 106.875 ° E, 43.75 to 78.75 ° N, East Russia 103.125 to 189.375 ° E, 43.75 to 78.75 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Country split for presentation purposes only.
Saudi Arabia	31.875 to 54.375 ° E, 16.25 to 33.75 ° N	HadEX (T,P)	1960-2000 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT	annual	Spatial coverage is poor
South Africa	13.125 to 35.625 ° W, 21.25 to 36.25 ° S	HadEX (T,P)	1960-2000 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	---
Republic of Korea	125.625 to 129.375 ° E, 33.75 to 38.75 ° N	HadEX (T,P)	1960-2003 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD	annual	There are too few data points for CWD to calculate trends or regional timeseries
Spain	9.375 ° W to 1.875 ° E, 36.25 to 43.75 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
Turkey	24.375 to 46.875 ° E, 36.25 to 43.75 ° N	HadEX (T,P)	1960-2003 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	Intermittent coverage in CWD and CDD with no regional average beyond 2000
United Kingdom	9.375 ° W to 1.875 ° E, 51.25 to 58.75 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
United States of America	125.625 to 65.625 ° W, 23.75 to 48.75 ° N	GHCND (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	

Table 5. Summary of data used for each country

Quality control and gridding procedure used for updates to the HadEX analysis of extremes

In order to perform some basic quality control checks on the index data, we used a two-step process on the indices. Firstly, internal checks were carried out, to remove cases where the 5 day rainfall value is less than the 1 day rainfall value, the minimum T_min is greater than the minimum T_max and the maximum T_min is greater than the maximum T_max.

Although these are physically impossible, they could arise from transcription errors when creating the daily dataset, for example, a misplaced minus sign, an extra digit appearing in the record or a column transposition during digitisation. During these tests we also require that there are at least 20 years of data in the period of record for the index for that station, and that some data is found in each decade between 1961 and 1990, to allow a reasonable estimation of the climatology over that period.

Weather conditions are often similar over many tens of kilometres and the indices calculated in this work are even more coherent. The correlation coefficient between each station-pair combination in all the data obtained is calculated for each index (and month where appropriate), and plotted as a function of the separation. An exponential decay curve is fitted to the data, and the distance at which this curve has fallen by a factor $1/e$ is taken as the decorrelation length scale (DLS). A DLS is calculated for each dataset separately. For the GHCND, a separate DLS is calculated for each hemisphere. We do not force the fitted decay curve to show perfect correlation at zero distance, which is different to the method employed when creating HadEX. For some of the indices in some countries, no clear decay pattern was observed in some data sets or the decay was so slow that no value for the DLS could be determined. In these cases a default value of 200km was used.

We then perform external checks on the index data by comparing the value for each station with that of its neighbours. As the station values are correlated, it is therefore likely that if one station measures a high value for an index for a given month, its neighbours will also be measuring high. We exploit this coherence to find further bad values or stations as follows. Although raw precipitation data shows a high degree of localisation, using indices which have monthly or annual resolution improves the coherence across wider areas and so this neighbour checking technique is a valid method of finding anomalous stations.

We calculate a climatology for each station (and month if appropriate) using the mean value for each index over the period 1961-1990. The values for each station are then anomalised using this climatology by subtracting this mean value from the true values, so that it is clear if the station values are higher or lower than normal. This means that we do not need to take

differences in elevation or topography into account when comparing neighbours, as we are not comparing actual values, but rather deviations from the mean value.

All stations which are within the DLS distance are investigated and their anomalised values noted. We then calculate the weighted median value from these stations to take into account the decay in the correlation with increasing distance. We use the median to reduce the sensitivity to outliers.

If the station value is greater than 7.5 median-absolute-deviations away from the weighted median value (this corresponds to about 5 standard deviations if the distribution is Gaussian, but is a robust measure of the spread of the distribution), then there is low confidence in the veracity of this value and so it is removed from the data.

To present the data, the individual stations are gridded on a $3.75^\circ \times 2.5^\circ$ grid, matching the output from HadCM3. To determine the value of each grid box, the DLS is used to calculate which stations can reasonably contribute to the value. The value of each station is then weighted using the DLS to obtain a final grid box value. At least three stations need to have valid data and be near enough (within 1 DLS of the gridbox centre) to contribute in order for a value to be calculated for the grid point. As for the original HadEX, the HadCM3 land-sea mask is used. However, in three cases the mask has been adjusted as there are data over Tasmania, eastern Australia and Italy that would not be included otherwise (Figure 6).

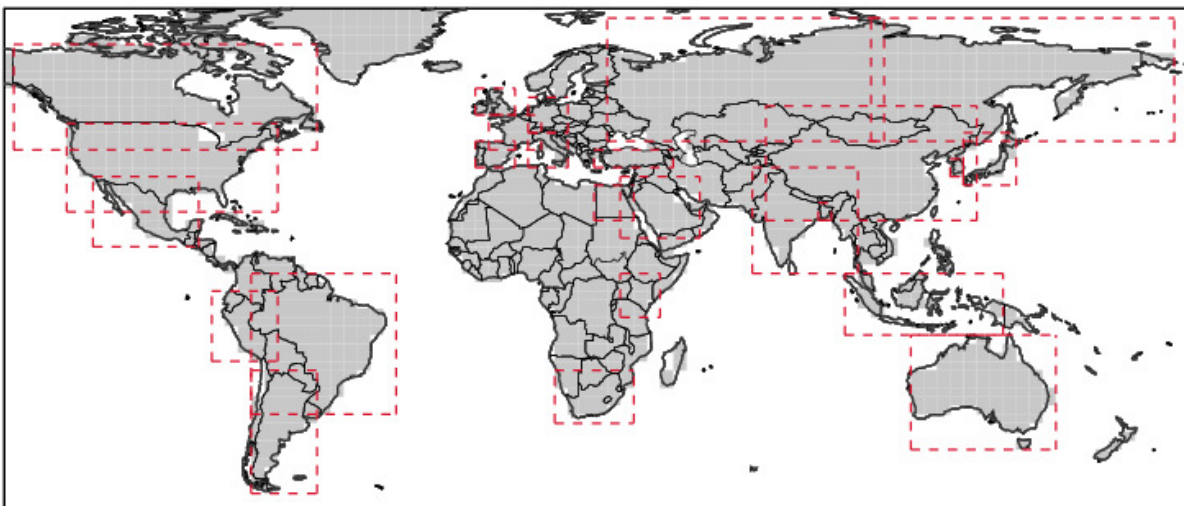


Figure 6. Land Sea mask used for gridding the station data and regional areas allocated to each country as described in Table 5.

Presentation of extremes of temperature and precipitation

Indices are displayed as regional gridded maps of decadal trends and regional average time-series with decadal trends where appropriate. Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). Trends are considered to be significantly different from a zero trend if the 5th to 95th percentiles of the pairwise slopes do not encompass zero. This is shown by a black dot in the centre of the grid-box or by a solid line on time-series plots. This infers that there is high confidence in the sign (positive or negative) of the sign. Confidence in the trend magnitude can be inferred by the spread of the 5th to 95th percentiles of the pairwise slopes which is given for the regional average decadal trends. Trends are only calculated when there are data present for at least 50% of years in the period of record and for the updated data (not HadEX) there must be at least one year in each decade.

Due to the practice of data-interpolation during the gridding stage (using the DLS) there are values for some grid boxes when no actually station lies within the grid box. There is more confidence in grid boxes for which there are underlying data. For this reason, we identify those grid boxes which contain at least 3 stations by a black contour line on the maps. The DLS differs with region, season and index which leads to large differences in the spatial coverage. The indices, by their nature of being largely threshold driven, can be intermittent over time which also effects spatial and temporal coverage (see Table 4).

Each index (and each month for the indices for which there is monthly data) has a different DLS, and so the coverage between different indices and datasets can be different. The restrictions on having at least 20 years of data present for each input station, at least 50% of years in the period of record and at least one year in each decade for the trending calculation, combined with the DLS, can restrict the coverage to only those regions with a dense station network reporting reliably.

Each country has a rectangular region assigned as shown by the red dashed box on the map in Figure 6 and listed in Table 5, which is used for the creation of the regional average. This is sometimes identical to the attribution region shown in grey on the map in Figure 6. This region is again shown on the maps accompanying the time series of the regional averages as a reminder of the region and grid boxes used in the calculation. Regional averages are created by weighting grid box values by the cosine of their grid box centre latitude. To ensure consistency over time a regional average is only calculated when there are a sufficient number of grid boxes present. The full-period median number of grid-boxes present is calculated. For regions with a median of more than six grid-boxes there must be at least 80%

of the median number of grid boxes present for any one year to calculate a regional average. For regions with six or fewer median grid boxes this is relaxed to 50%. These limitations ensure that a single station or grid box which has a longer period of record than its neighbours cannot skew the timeseries trend. So sometimes there may be grid-boxes present but no regional average time series. The trends for the regional averages are calculated in the same way as for the individual grid boxes, using the median of pairwise slopes method (Sen 1968, Lanzante 1996). Confidence in the trend is also determined if the 5th to 95th percentiles of the pairwise slopes are of the same sign and thus inconsistent with a zero trend. As well as the trend in quantity per decade, we also show the full change in the quantity from 1960 to 2010 that this fitted linear trend implies.

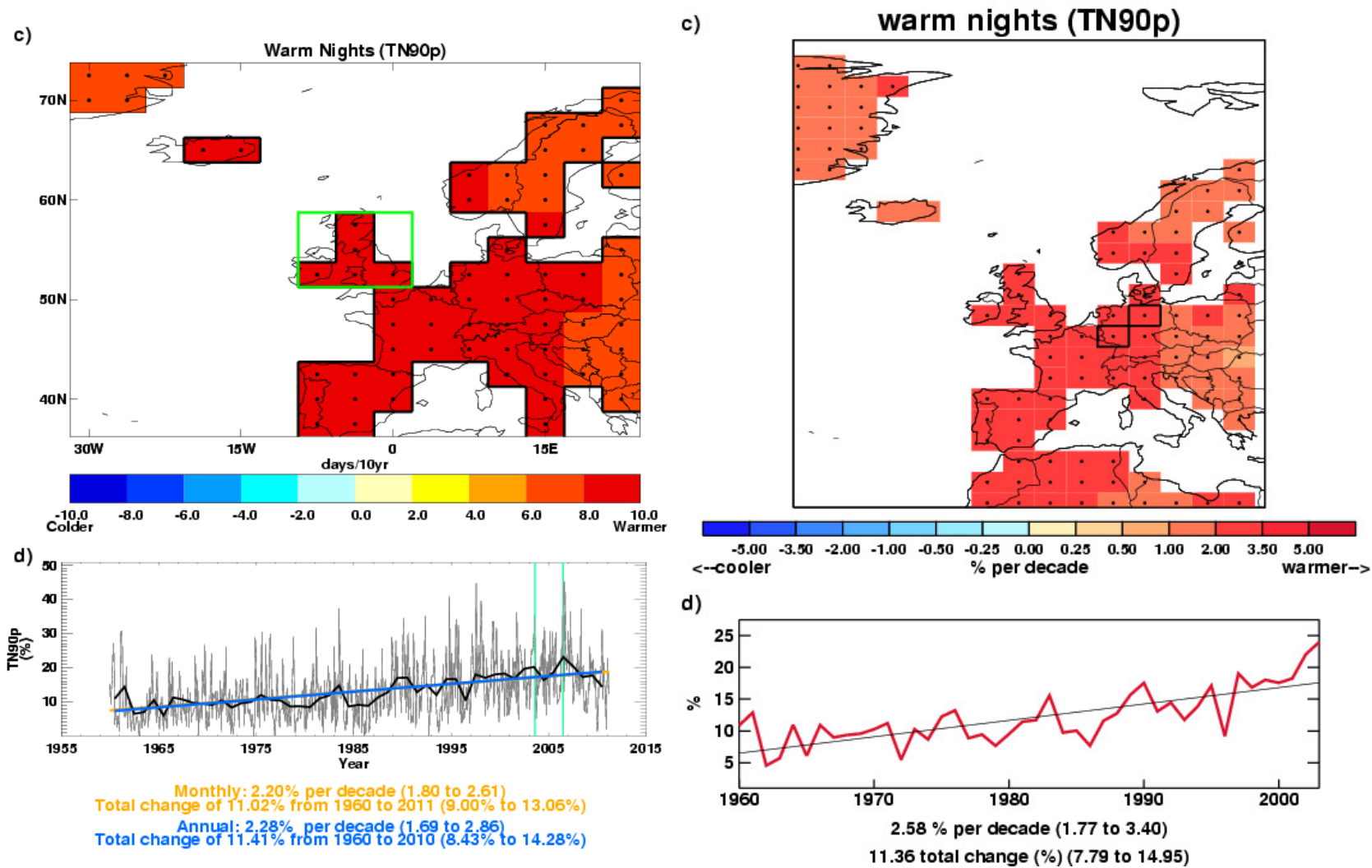


Figure 7. Examples of the plots shown in the data section. Left: From ECA&D data between 1960-2010 for the number of warm nights, and Right: from HadEX data (1960-2003) for the total precipitation. A full explanation of the plots is given in the text below.

The results are presented in the form of a map and a time series for each country and index. The map shows the grid box decadal trend in the index over the period for which there are data. High confidence, as determined above, is shown by a black dot in the grid box centre. To show the variation over time, the values for each year (and month if available) are shown in a time series for a regional average. The values of the indices have been normalised to a base period of 1961-1990 (except the Indian gridded data which use a 1971 to 1990 period), both in HadEX and in the new data acquired for this project. Therefore, for example, the percentage of nights exceeding the 90th percentile for a temperature is 10% for that period.

There are two influences on whether a grid box contains a value or not – the land-sea mask, and the decorrelation length scale. The land-sea mask is shown in Figure 6. There are grid boxes which contain some land but are mostly sea and so are not considered. The decorrelation length scale sets the maximum distance a grid box can be from stations before no value is assigned to it. Grid boxes containing three or more stations are highlighted by a thick border. This indicates regions where the value shown is likely to be more representative of the grid box area mean as opposed to a single station location.

On the maps for the new data there is a box indicating which grid boxes have been extracted to calculate the area average for the time series. This box is the same as shown in Figure 6 at the beginning of each country's document. These selected grid boxes are combined using area (cosine) weighting to calculate the regional average (both annual [thick lines] and monthly [thin lines] where available). Monthly (orange) and annual (blue) trends are fitted to these time series using the method described above. The decadal trend and total change over the period where there are data are shown with 5th to 95th percentile confidence intervals in parentheses. High confidence, as determined above, is shown by a solid line as opposed to a dotted one. The green vertical lines on the time series show the dates of some of the notable events outlined in each section.

Attribution

Regional distributions of seasonal mean temperatures in the 2000s are computed with and without the effect of anthropogenic influences on the climate. The analysis considers temperatures averaged over the regions shown in Figure 8. These are also identified as grey boxes on the maps in Figure 6. The coordinates of the regions are given in Table 6. The methodology combines information from observations and model simulations using the approach originally introduced in Christidis et al., 2010 and later extended in Christidis et al., 2011, where more details can be found. The analysis requires spatial scales greater than about 2,500 km and for that reason the selected regions (Fig.6 and Table 8) are often larger

than individual countries, or include several smaller countries in a single region (for example UK, Germany and France are grouped in one region).

Observations of land temperature come from the CRUTEM3 gridded dataset (Brohan et al., 2006) and model simulations from two coupled GCMs, namely the Hadley Centre HadGEM1 model (Martin et al., 2006) and version 3.2 of the MIROC model (K-1 Developers, 2004). The use of two GCMs helps investigate the sensitivity of the results to the model used in the analysis. Ensembles of model simulations from two types of experiments are used to partition the temperature response to external forcings between its anthropogenic and natural components. The first experiment (ALL) simulates the combined effect of natural and anthropogenic forcings on the climate system and the second (ANTHRO) includes anthropogenic forcings only. The difference of the two gives an estimate of the effect of the natural forcings (NAT). Estimates of the effect of internal climate variability are derived from long control simulations of the unforced climate. Distributions of the regional summer mean temperature are computed as follows:

- a) A global optimal fingerprinting analysis (Allen and Tett, 1999; Allen and Stott, 2003) is first carried out that scales the global simulated patterns (fingerprints) of climate change attributed to different combinations of external forcings to best match them to the observations. The uncertainty in the scaling that originates from internal variability leads to samples of the scaled fingerprints, i.e. several realisations that are plausibly consistent with the observations. The 2000-2009 decade is then extracted from the scaled patterns and two samples of the decadal mean temperature averaged over the reference region are then computed with and without human influences, which provide the Probability Density Functions (PDFs) of the decadal mean temperature attributable to ALL and NAT forcings.
- b) Model-derived estimates of noise are added to the distributions to take into account the uncertainty in the simulated fingerprints.
- c) In the same way, additional noise from control model simulations is introduced to the distributions to represent the effect of internal variability in the annual values of the seasonal mean temperatures. The result is a pair of estimated distributions of the annual values of the seasonal mean temperature in the region with and without the effect of human activity on the climate. The temperatures throughout the analysis are expressed as anomalies relative to period 1961-1990.

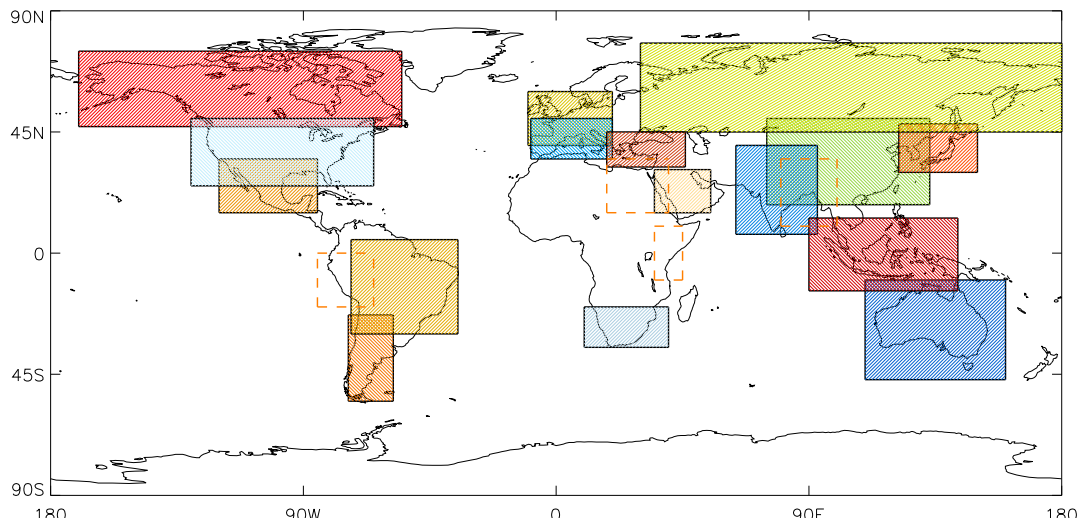


Figure 8. The regions used in the attribution analysis. Regions marked with dashed orange boundaries correspond to non-G20 countries that were also included in the analysis.

Region	Region Coordinates
Argentina	74-58W, 55-23S
Australia	110-160E, 47-10S
Bangladesh	80-100E, 10-35N
Brazil	73-35W, 30S-5N
Canada-Alaska	170-55W, 47-75N
China	75-133E, 18-50N
Egypt	18-40E, 15-35N
France-Germany-UK	10W-20E, 40-60N
India	64-93E, 7-40N
Indonesia	90-143E, 14S-13N
Italy-Spain	9W-20E, 35-50N
Japan-Republic of Korea	122-150E, 30-48N
Kenya	35-45E, 10S-10N
Mexico	120-85W, 15-35N
Peru	85-65W, 20-0S
Russia	30-185E, 45-78N
Saudi Arabia	35-55E, 15-31N
South Africa	10-40E, 35-20S
Turkey	18-46E, 32-45N

Table 6. The coordinates of the regions used in the attribution analysis.

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Chapter 2 – Climate Change Projections

Introduction

Climate models are used to understand how the climate will evolve over time and typically represent the atmosphere, ocean, land surface, cryosphere, and biogeochemical processes, and solve the equations governing their evolution on a geographical grid covering the globe. Some processes are represented explicitly within climate models, large-scale circulations for instance, while others are represented by simplified parameterisations. The use of these parameterisations is sometimes due to processes taking place on scales smaller than the typical grid size of a climate model (a Global Climate Model (GCM) has a typical horizontal resolution of between 250 and 600km) or sometimes to the current limited understanding of these processes. Different climate modelling institutions use different plausible representations of the climate system, which is why climate projections for a single greenhouse gas emissions scenario differ between modelling institutes. This gives rise to “climate model structural uncertainty”.

In response to a proposed activity of the World Climate Research Programme's (WCRP's; <http://www.wcrp-climate.org/>) Working Group on Coupled Modelling (WGCM), the Program for Climate Model Diagnosis and Intercomparison (PCMDI; <http://www-pcmdi.llnl.gov/>) volunteered to collect model output contributed by leading climate modelling centres around the world. Climate model output from simulations of the past, present and future climate was collected by PCMDI mostly during the years 2005 and 2006, and this archived data constitutes phase 3 of the Coupled Model Intercomparison Project (CMIP3). In part, the WGCM organised this activity to enable those outside the major modelling centres to perform research of relevance to climate scientists preparing the IPCC Fourth Assessment Report (AR4). This unprecedented collection of recent model output is commonly known as the “CMIP3 multi-model dataset”. The GCMs included in this dataset are referred to regularly throughout this review, although not exclusively.

The CMIP3 multi-model ensemble has been widely used in studies of regional climate change and associated impacts. Each of the constituent models was subject to extensive testing by the contributing institute, and the ensemble has the advantage of having been constructed from a large pool of alternative model components, therefore sampling alternative structural assumptions in how best to represent the physical climate system. Being assembled on an opportunity basis, however, the CMIP3 ensemble was not designed to represent model uncertainties in a systematic manner, so it does not, in isolation, support robust estimates of the risk of different levels of future climate change, especially at a regional level.

Since CMIP3, a new (CMIP5) generation of coupled ocean-atmosphere models has been developed, which is only just beginning to be available and is being used for new projections for the IPCC Fifth Assessment Report (AR5).

These newer models typically feature higher spatial resolution than their CMIP3 counterparts, including in some models a more realistic representation of stratosphere-troposphere interactions. The CMIP5 models also benefit from several years of development in their parameterisations of small scale processes, which, together with resolution increases, are expected to result in a general improvement in the accuracy of their simulations of historical climate, and in the credibility of their projections of future changes. The CMIP5 programme also includes a number of comprehensive Earth System Models (ESMs) which explicitly simulate the earth's carbon cycle and key aspects of atmospheric chemistry, and also contain more sophisticated representations of aerosols compared to CMIP3 models.

The CMIP3 results should be interpreted as a useful interim set of plausible outcomes. However, their neglect of uncertainties, for instance in carbon cycle feedbacks, implies that higher levels of warming outside the CMIP3 envelope cannot be ruled out. In future, CMIP5 coupled model and ESM projections can be expected to produce improved advice on future regional changes. In particular, ensembles of ESM projections will be needed to provide a more comprehensive survey of possible future changes and their relative likelihoods of occurrence. This is likely to require analysis of the CMIP5 multi-model ESM projections, augmented by larger ensembles of ESM simulations in which uncertainties in physical and biogeochemical feedback processes can be explored more systematically, for example via ensembles of model runs in which key aspects of the climate model are slightly adjusted. Note that such an exercise might lead to the specification of wider rather than narrower uncertainties compared to CMIP3 results, if the effects of representing a wider range of earth system processes outweigh the effects of refinements in the simulation of physical atmosphere-ocean processes already included in the CMIP3 models.

Climate projections

The Met Office Hadley Centre is currently producing perturbed parameter ensembles of a single model configuration known as HadCM3C, to explore uncertainties in physical and biogeochemical feedback processes. The results of this analysis will become available in the next year and will supplement the CMIP5 multi-model ESM projections, providing a more comprehensive set of data to help progress understanding of future climate change.

However, many of the studies covered in the chapter on climate impacts have used CMIP3 model output. For this reason, and because it is still the most widely used set of projections available, the CMIP3 ensemble output for temperature and precipitation, for the A1B emission scenario, for Australia and the surrounding region is shown below.

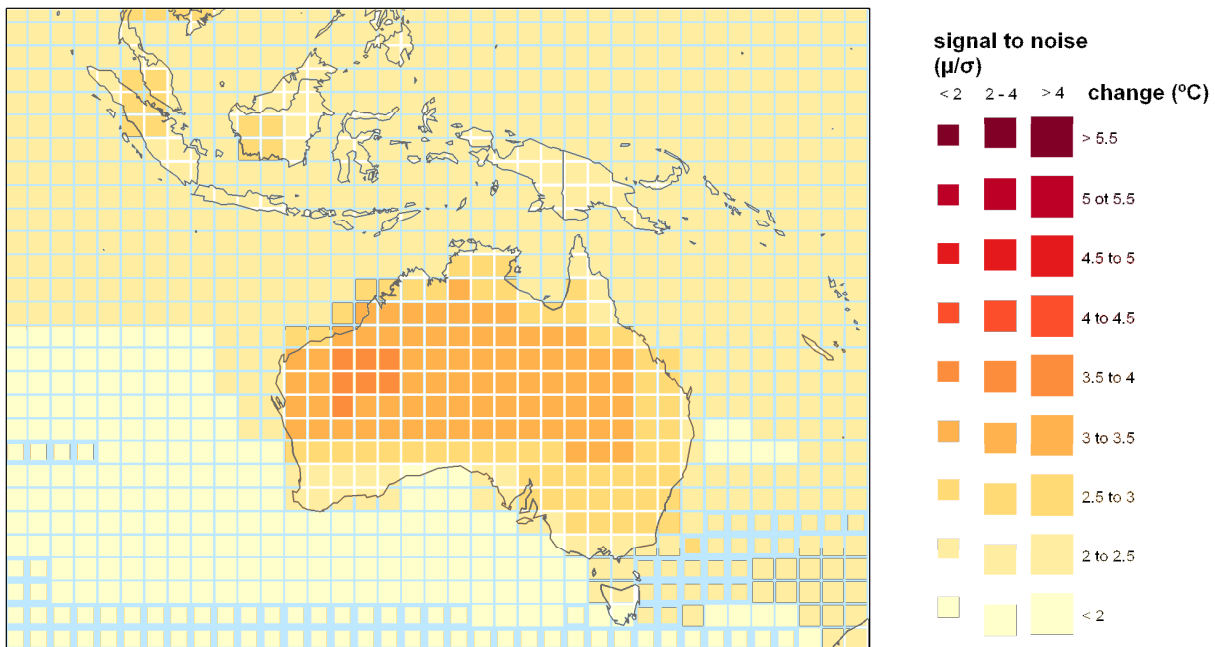


Figure 1. Percentage change in average annual temperature by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the magnitude of the change.

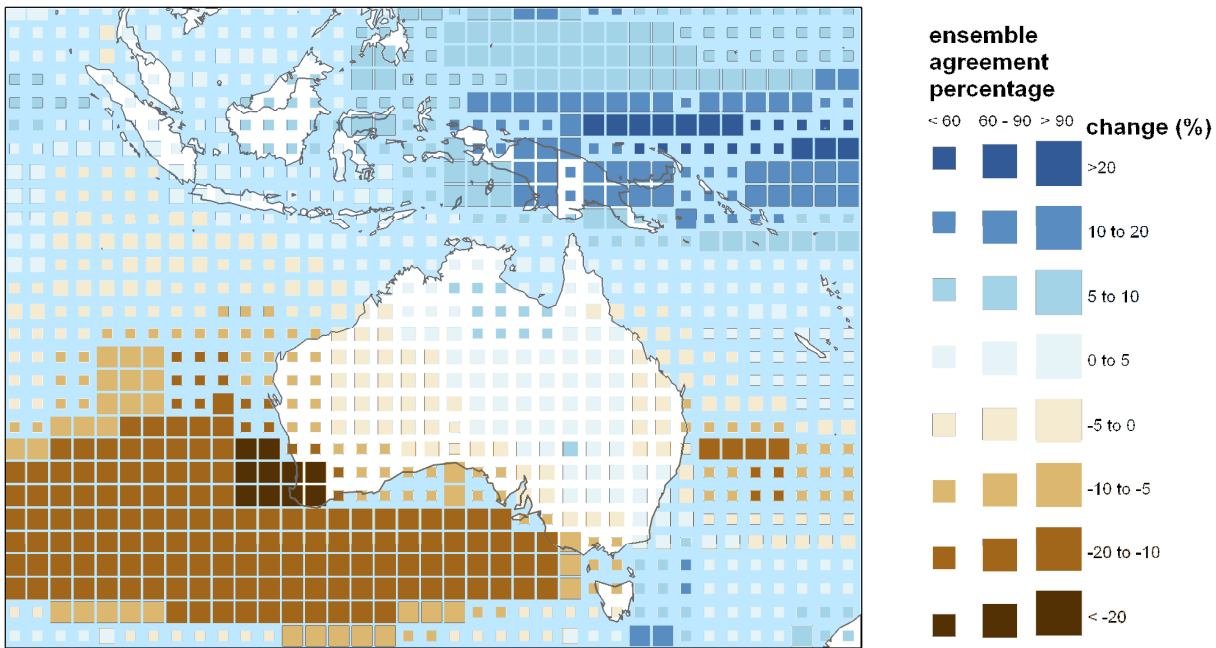


Figure 2. Percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the sign of the change.

Summary of temperature change in Australia

Figure 1 shows the percentage change in average annual temperature by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. All of the models in the CMIP3 ensemble project increased temperatures in the future, but the size of each pixel indicates how well the models agree over the magnitude of the increase.

Projected temperature increases are larger over central and western regions of Australia, with changes of up to around 4°C. Along most of the coastal regions, changes of around 2.5°C are more typical. There is good agreement between the models over all of Australia.

Summary of precipitation change in Australia

Figure 2 shows the percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. Unlike for temperature, the models sometimes disagree over whether precipitation is increasing or decreasing over a region, so in this case the size of each pixel indicates the percentage of the models in the ensemble that agree on the sign of the change in precipitation.

For precipitation changes, there is moderate to low agreement amongst the ensemble of models. Decreases of around 20% or more are projected over some parts of the far west,

but moderate decreases of around 5% are more typical over most of Western Australia, as well as eastern Queensland, Victoria, and southern South Australia. Much of the Northern Territory, Queensland, and parts of New South Wales are projected to experience increases of up to 5%, with increases of up to 10% in the far north.

Chapter 3 - Climate Change Impact Projections

Introduction

Aims and approach

This chapter looks at research on a range of projected climate change impacts, with focus on results for Australia. It includes projections taken from the AVOID programme, for some of the impact sectors.

The aim of this work is to take a 'top down' approach to assessing global impacts studies, both from the literature and from new research undertaken by the AVOID programme. This project covers 23 countries, with summaries from global studies provided for each of these. This global approach allows some level of comparison between countries, whilst presenting information on a scale most meaningful to inform international policy.

The literature covered in this chapter focuses on research published since the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) and should be read in conjunction with IPCC AR4 WG1 and WG2 reports. For some sectors considered, an absence of research developments since the IPCC AR4, means earlier work is cited as this helps describe the current level of scientific understanding. This report focuses on assessing scientific research about climate change impacts within sectors; it does not present an integrated analysis of climate change adaptation policies.

Some national and sub-national scale literature is reported to a limited extent to provide some regional context.

Impact sectors considered and methods

This report reviews the evidence for the impact of climate change on a number of sectors, for Australia. The following sectors are considered in turn in this report:

- Crop yields
- Food security
- Water stress and drought
- Pluvial flooding and rainfall
- Fluvial flooding

- Tropical cyclones (where applicable)
- Coastal regions

Supporting literature

Literature searches were conducted for each sector with the Thomson Reuters Web of Science (WoS., 2011) and Google Scholar academic search engines respectively. Furthermore, climate change impact experts from each of the 23 countries reviewed were contacted. These experts were selected through a combination of government nomination and from experts known to the Met Office. They were asked to provide literature that they felt would be of relevance to this review. Where appropriate, such evidence has been included. A wide range of evidence was considered, including; research from international peer-reviewed journal papers; reports from governments, non-governmental organisations, and private businesses (e.g. reinsurance companies), and research papers published in national journals.

For each impact sector, results from assessments that include a global- or regional-scale perspective are considered separately from research that has been conducted at the national- or sub-national-scale. The consideration of global- and regional-scale studies facilitates a comparison of impacts across different countries, because such studies apply a consistent methodology for each country. While results from national- and sub-national-scale studies are not easily comparable between countries, they can provide a level of detail that is not always possible with larger-scale studies. However, the national- and sub-national scale literature included in this project does not represent a comprehensive coverage of regional-based research and cannot, and should not, replace individual, detailed impacts studies in countries. The review aims to present an up-to-date assessment of the impact of climate change on each of the sectors considered.

AVOID programme results

Much of the work in this report is drawn from modelling results and analyses coming out of the AVOID programme. The AVOID programme is a research consortium funded by DECC and Defra and led by the UK Met Office and also comprises the Walker Institute at the University of Reading, the Tyndall Centre represented through the University of East Anglia, and the Grantham Institute for Climate Change at Imperial College. The expertise in the AVOID programme includes climate change research and modelling, climate change impacts in natural and human systems, socio-economic sciences, mitigation and technology.

The unique expertise of the programme is in bringing these research areas together to produce integrated and policy-relevant results. The experts who work within the programme were also well suited to review the literature assessment part of this report. In this report the modelling of sea level rise impacts was carried out for the AVOID programme by the University of Southampton.

The AVOID programme uses the same emissions scenarios across the different impact sectors studied. These are a business as usual (IPCC SRES A1B) and an aggressive mitigation (the AVOID A1B-2016-5-L) scenario. Model output for both scenarios was taken from more than 20 GCMs and averaged for use in the impact models. The impact models are sector specific, and frequently employ further analytical techniques such as pattern scaling and downscaling in the crop yield models.

Data and analysis from AVOID programme research is provided for the following impact sectors:

- Crop yields
- Water stress and drought
- Fluvial flooding
- Coastal regions

Uncertainty in climate change impact assessment

There are many uncertainties in future projections of climate change and its impacts. Several of these are well-recognised, but some are not. One category of uncertainty arises because we don't yet know how mankind will alter the climate in the future. For instance, uncertainties in future greenhouse gas emissions depends on the future socio-economic pathway, which, in turn, depends on factors such as population, economic growth, technology development, energy demand and methods of supply, and land use. The usual approach to dealing with this is to consider a range of possible future scenarios.

Another category of uncertainties relate to our incomplete understanding of the climate system, or an inability to adequately model some aspects of the system. This includes:

- Uncertainties in translating emissions of greenhouse gases into atmospheric concentrations and radiative forcing. Atmospheric CO₂ concentrations are currently rising at approximately 50% of the rate of anthropogenic emissions, with the

remaining 50% being offset by a net uptake of CO₂ into the oceans and land biosphere. However, this rate of uptake itself probably depends on climate, and evidence suggests it may weaken under a warming climate, causing more CO₂ to remain in the atmosphere, warming climate further. The extent of this feedback is highly uncertain, but it not considered in most studies. The phase 3 of the Coupled Model Intercomparison Project (CMIP3), which provided the future climate projections for the IPCC Fourth Assessment Report (AR4), used a single estimate of CO₂ concentration rise for each emissions scenario, so the CMIP3 projections (which were used in most studies presented here, including AVOID) do not account for this uncertainty.

- Uncertainty in climate response to the forcing by greenhouse gases and aerosols. One aspect of this is the response of global mean temperature (“climate sensitivity”), but a more relevant aspect for impacts studies is the response of regional climates, including temperature, precipitation and other meteorological variables. Different climate models can give very different results in some regions, while giving similar results in other regions. Confidence in regional projections requires more than just agreement between models: physical understanding of the relevant atmospheric, ocean and land surface processes is also important, to establish whether the models are likely to be realistic.
- Additional forcings of regional climate. Greenhouse gas changes are not the only anthropogenic driver of climate change; atmospheric aerosols and land cover change are also important, and unlike greenhouse gases, the strength of their influence varies significantly from place to place. The CMIP3 models used in most impacts studies generally account for aerosols but not land cover change.
- Uncertainty in impacts processes. The consequences of a given changes in weather or climatic conditions for biophysical impacts such as river flows, drought, flooding, crop yield or ecosystem distribution and functioning depend on many other processes which are often poorly-understood, especially at large scales. In particular, the extent to which different biophysical impacts interact with each other has been hardly studied, but may be crucial; for example, impacts of climate change on crop yield may depend not only on local climate changes affecting rain-fed crops, but also remote climate changes affecting river flows providing water for irrigation.
- Uncertainties in non-climate effects of some greenhouse gases. As well as being a greenhouse gas, CO₂ exerts physiological influences on plants, affecting

photosynthesis and transpiration. Under higher CO₂ concentrations, and with no other limiting factors, photosynthesis can increase, while the requirements of water for transpiration can decrease. However, while this has been extensively studied under experimental conditions, including in some cases in the free atmosphere, the extent to which the ongoing rise in ambient CO₂ affects crop yields and natural vegetation functioning remains uncertain and controversial. Many impacts projections assume CO₂ physiological effects to be significant, while others assume it to be non-existent. Studies of climate change impacts on crops and ecosystems should therefore be examined with care to establish which assumptions have been made.

In addition to these uncertainties, the climate varies significantly through natural processes from year-to-year and also decade-to-decade, and this variability can be significant in comparison to anthropogenic forcings on shorter timescales (the next few decades) particularly at regional scales. Whilst we can characterise the natural variability it will not be possible to give a precise forecast for a particular year decades into the future.

A further category of uncertainty in projections arises as a result of using different methods to correct for uncertainties and limitations in climate models. Despite being painstakingly developed in order to represent current climate as closely as possible, current climate models are nevertheless subject to systematic errors such as simulating too little or too much rainfall in some regions. In order to reduce the impact of these, '*bias correction*' techniques are often employed, in which the climate model is a source of information on the *change* in climate which is then applied to the observed present-day climate state (rather than using the model's own simulation of the present-day state). However, these bias-corrections typically introduce their own uncertainties and errors, and can lead to inconsistencies between the projected impacts and the driving climate change (such as river flows changing by an amount which is not matched by the original change in precipitation). Currently, this source of uncertainty is rarely considered.

When climate change projections from climate models are applied to climate change impact models (e.g. a global hydrological model), the climate model structural uncertainty carries through to the impact estimates. Additional uncertainties include changes in future emissions and population, as well as parameterisations within the impact models (this is rarely considered). Figure 1 highlights the importance of considering climate model structural uncertainty in climate change impacts assessment. Figure 1 shows that for 2°C prescribed global-mean warming, the magnitude of, and sign of change in average annual runoff from present, simulated by an impacts model, can differ depending upon the GCM that provides

the climate change projections that drive the impact model. This example also shows that the choice of impact model, in this case a global hydrological model (GHM) or catchment-scale hydrological model (CHM), can affect the magnitude of impact and sign of change from present (e.g. see IPSL CM4 and MPI ECHAM5 simulations for the Xiangxi). To this end, throughout this review, the number of climate models applied in each study reviewed, and the other sources of uncertainty (e.g. emissions scenarios) are noted. Very few studies consider the application of multiple impacts models and it is recommended that future studies address this.

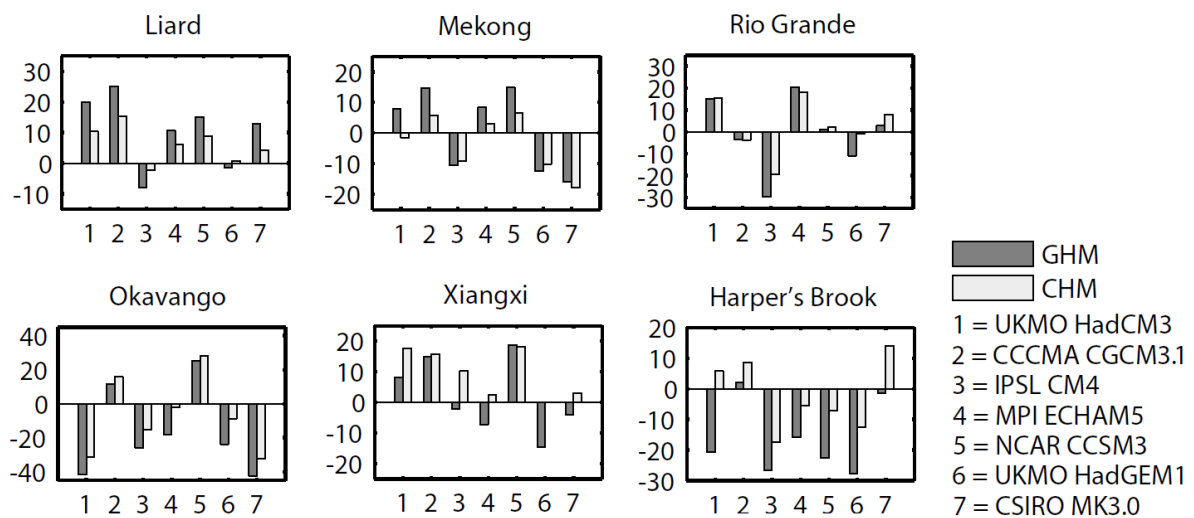


Figure 1. Change in average annual runoff relative to present (vertical axis; %), when a global hydrological model (GHM) and a catchment-scale hydrological model (CHM) are driven with climate change projections from 7 GCMs (horizontal axis), under a 2 °C prescribed global-mean warming scenario, for six river catchments. The figure is from Gosling et al. (2011).

Uncertainties in the large scale climate relevant to Australia includes changes in the El Niño-Southern Oscillation (ENSO) which could undergo rapid change with climate change. This could have a serious impact on large-scale atmospheric circulation, rainfall and seasonality in many parts of the world. Latif and Keenlyside (2009) concluded that, at this stage of understanding, it is not known how climate change might affect the tropical Pacific climate system. None of the global climate models (GCMs) they analysed showed rapid changes in behaviour. However, a threshold of abrupt change cannot be ruled out because whilst the GCMs that Latif and Keenlyside (2009) analysed (the CMIP3 multi-model dataset) are better than the previous generation of models (Reichler and Kim, 2008), these same models all show large biases in simulating the contemporary tropical Pacific, with no consensus on the sign of change in ENSO-like response.

Summary of findings for each sector

Crop yields

- Quantitative crop yield projections under climate change scenarios for Australia vary across studies due to the application of different models, assumptions and emissions scenarios.
- A number of global- and regional-scale studies included here project yield increases in the near and medium future for wheat, one of the country's major crops, although this is not true for all studies.
- However, simulations by the AVOID programme indicate that, of the land currently cultivated in Australia, much of it could become less suitable for agricultural production as a result of climate change.
- National-scale studies highlight sub-regional variation in the vulnerability of crop yields to climate change and moreover a need for implementation of adaptation strategies to cope with climate change, particularly for the rice and grape wine industries.
- Important knowledge gaps and key uncertainties include the quantification of yield increases due to CO₂ fertilisation, quantification of yield reductions due to ozone damage and the extent to which crop diseases might affect crop yields with climate change.

Food security

- Australia is currently a country of extremely low undernourishment. Global-scale studies included here project that the country as a whole may remain food secure over the next 40 years, partly due to the country's strong purchasing power and adaptive capacity.
- One study concluded that the national economy of Australia presents a very low vulnerability to climate change impacts on fisheries by the 2050s. Another projects a small increase (~3%) in maximum fish catch potential may be possible by the 2050s under SRES A1B.

Water stress and drought

- The global and regional assessments included here show a high degree of uncertainty regarding how water availability in Australia could be affected by climate change. This is mainly due to different GCMs simulating changes of different sign with climate change, but also due to studies considering different indicators of water stress.
- However, there is some consensus that south-eastern Australia could become drier with climate change, which could increase water stress in this region. This could be exacerbated by increasing population pressures.
- Recent simulations by the AVOID programme do not project an increase or decrease in the exposure of Australia's population to water stress with climate change.

Pluvial flooding and rainfall

- The projections described in the IPCC AR4 noted a tendency for reducing rainfall over many regions of Australia but that extremes may increase.
- Work since then generally agrees with this, but has highlighted differences and uncertainties in changes at the regional level. These are largely a result of inconsistencies in model projections, and also incomplete understanding of how climate change will influence large-scale systems such as the El-Niño Southern Oscillation, the large-scale monsoon system, and changes to tropical cyclones.

Fluvial flooding

- Floods in Queensland and New South Wales in December 2010 were the most significant in Australia since at least the 1970s in terms of extent and impact.
- However, there is large uncertainty in projections of fluvial flooding for Australia under climate change, largely due to climate modelling uncertainty.
- Some models project an increase in river discharge and some project a decrease.
- Recent simulations by the AVOID programme confirm this uncertainty. A majority of the simulations showing a decreasing trend in flood risk by the 2030s, but with increasing uncertainty in projections through the century.

- Improved hydro-climate projections, with reliable probabilistic quantification of uncertainties, could help make more informed risk-based water sharing and management decisions.

Tropical cyclones

- There remains large uncertainty in the current understanding of how tropical cyclones might be affected by climate change, including in the Pacific and South Indian Ocean basins as conclusions are based upon a limited number of studies whose projections are from either coarse-resolution global models or from statistical or dynamical downscaling techniques. To this end, caution should be applied in interpreting model-based results, even where the models are in agreement.
- A review of the current literature suggests that the frequency of tropical cyclones in the Southwest Pacific and South Indian Ocean basins could decrease in a warmer world, reducing the overall probability of tropical cyclone landfall on Australia's east and west coasts, respectively.
- A southward shift in tropical cyclone tracks has been reported by several studies included here, which may increase the risk of damage from landfalling cyclones near Australia's more heavily populated cities.
- A number of recent studies included here suggest that tropical cyclone intensities may increase with climate change, which could place vulnerable communities in the Torres Strait Islands at risk.

Coastal regions

- Australia is characterised by densely and increasingly populated coastal areas; 80% of the population live within 50 km of the coast.
- Several studies suggest that Sea Level Rise (SLR) could increase coastal flooding in Australia. However, the absolute magnitude of the simulated impacts tend to be relatively small when compared with other countries across the globe.
- This is due to several assumptions, including:
 - A decline in population growth from 2050 onwards
 - An increase in GDP and coastal protection in the future
 - An improved adaptive capacity for the region as a whole in the future

Crop yields

Headline

The majority of assessments of the impact of climate change on crop yields for Australia focus on wheat. Generally, crop yield projections for Australia vary greatly across studies due to the application of different models, assumptions and emissions scenario. However, model projections tend to show yield increases in the near and medium future for wheat. National-scale studies highlight sub-regional variation in vulnerability of crop yields to climate change and moreover a need for implementation of adaptation strategies to cope with climate change, particularly for the rice and grape wine industries.

The AVOID programme results for Australia suggest that nearly all croplands could experience an early and sustained decline in suitability even under the mitigation scenario. However, some models project smaller areas of land seeing decline than others. There is little difference between the A1B emission scenario and the aggressive mitigation scenario.

Supporting literature

Introduction

The impacts of climate change on crop productivity are highly uncertain due to the complexity of the processes involved. Most current studies are limited in their ability to capture the uncertainty in regional climate projections, and often omit potentially important aspects such as extreme events and changes in pests and diseases. Importantly, there is a lack of clarity on how climate change impacts on drought are best quantified from an agricultural perspective, with different metrics giving very different impressions of future risk. The dependence of some regional agriculture on remote rainfall, snowmelt and glaciers adds to the complexity - these factors are rarely taken into account, and most studies focus solely on the impacts of local climate change on rain-fed agriculture. However, irrigated agricultural land produces approximately 40-45 % of the world's food (Doll and Siebert 2002), and the water for irrigation is often extracted from rivers which can depend on climatic conditions far from the point of extraction. Hence, impacts of climate change on crop productivity often need to take account of remote as well as local climate changes. Indirect impacts via sea-level rise, storms and diseases have also not been quantified. Perhaps most seriously, there is high uncertainty in the extent to which the direct effects of CO₂ rise on plant physiology will interact with climate change in affecting productivity. Therefore, at present, the aggregate impacts of climate change on large-scale agricultural productivity cannot be reliably

quantified (Gornall et al, 2010). This section summarises findings from a range of post IPCC AR4 assessments to inform and contextualise the analysis performed by AVOID programme for this project. The results from the AVOID work are discussed in the next section.

Wheat and barley are the most important staple crops in Australia, in terms of harvested area, quantity as well as value (Table 1). Other important crops include sugar cane, sorghum, rapeseed and grapes.

Harvested area (ha)		Quantity (Metric ton)		Value (\$1000)	
Wheat	13500000	Sugar cane	32600000	Wheat	2650000
Barley	5010000	Wheat	21400000	Grapes	907000
Rapeseed	1690000	Barley	7990000	Sugar cane	677000
Sorghum	941000	Sorghum	3780000	Barley	548000
Oats	870000	Grapes	1950000	Rapeseed	522000
Lupins	573000	Rapeseed	1840000	Cotton lint	197000
Sugar cane	380000	Potatoes	1400000	Potatoes	183000

Table 1. The top 7 crops by harvested area, quantity and value according to the FAO (2008) in Australia. Crops that feature in all lists are shaded green; crops that feature in two top 7 lists are shaded amber. Data is from FAO (2008) and has been rounded down to three significant figures.

A number of impact model studies looking at crop yield which include results for some of the main crops in Australia have been conducted. They apply a variety of methodological approaches, including using different climate model inputs and treatment of other factors that might affect yield, such as impact of increased CO₂ in the atmosphere on plant growth and adaption of agricultural practises to changing climate conditions. These different models, assumptions and emissions scenarios mean that there are a range of crop yield projections for Australia.

Important knowledge gaps, which are applicable to Australia as well as at the global-scale, include; the quantification of yield increases due to CO₂ fertilisation and yield reductions due to ozone damage (Ainsworth and McGrath, 2010, Iglesias et al., 2009), and the extent crop diseases might affect crop yields with climate change (Luck et al., 2011).

Assessments that include a global or regional perspective

Recent past

Crop yield changes could be due to a variety of factors, which might include, but not be confined to, a changing climate. In order to assess the impact of recent climate change (1980-2008) on wheat, maize, rice and soybean, Lobell et al. (2011) looked at how the overall yield trend in these crops changed in response to changes in climate over the period studied. The study was conducted at the global-scale but national estimates for Australia were also calculated. Lobell et al. (2011) divided the climate-induced yield trend by the overall yield trend for 1980–2008, to produce a simple metric of the importance of climate relative to all other factors. The ratio produced indicates the influence of climate on the productivity trend overall. So for example a value of -0.1 represents a 10% reduction in yield gain due to climate change, compared to the increase that could have been achieved without climate change, but with technology and other gains. This can also be expressed as 10 years of climate trend being equivalent to the loss of roughly 1 year of technology gains. For Australia, positive and negative effects on wheat and soybean respectively were estimated relative to what could have been achieved without the climate trends (see Table 2).

Crop	Trend
Maize	0.0 - 0.1
Rice	0.0 - 0.1
Wheat	0.1 - 0.2
Soybean	-0.1 to -0.2

Table 2. The estimated net impact of climate trends for 1980-2008 on crop yields. Climate-induced yield trend divided by overall yield trend. 'n/a' infers zero or insignificant crop production or unavailability of data. Data is from Lobell et al. (Lobell et al., 2011).

Climate change studies

Global studies on changes in crop yield due to climate change covered in this report are derived mainly from applying Global Climate Model (GCM) output to crop models. The results for Australia are presented here.

Included in this report are recent studies have applied climate projections from GCMs to crop yield models to assess the global-scale impact of climate change on crop yields, and which include impact estimates at the national-scale for Australia (Iglesias and Rosenzweig, 2009, Fischer, 2009, Tatsumi et al., 2011). The process of CO₂ fertilisation of some crops is usually included in most climate impact studies of yields. However, other gases can influence crop yield and are not always included in impacts models. An example of this is ozone (O₃) and so a study which attempts to quantify the potential impact on crop yield of

changes in ozone in the atmosphere is also included (Avnery et al. 2011). In addition to these studies, the AVOID programme analysed the patterns of climate change for 21 GCMs, to establish an index of 'climate suitability' of agricultural land. Climate suitability is not directly equivalent to crop yields, but is a means of looking at a standard metric across all the countries included in this project, and of assessing the level of agreement on variables that affect crop production, between all 21 GCMs.

Iglesias and Rosenzweig (2009) repeated an earlier study presented by Parry et al. (2004) by applying climate projections from the HadCM3 GCM (instead of HadCM2, which was applied by Parry et al. (2004)), under seven SRES emissions scenarios and for three future time periods. This study used a globally consistent crop simulation methodologies and climate change scenarios, and weighted the model site results by their contribution to regional and national, and rain-fed and irrigated production. The study also applied a quantitative estimation of physiological CO₂ effects on crop yields and considered the affect of adaptation by assessing the country or regional potential for reaching optimal crop yield. The results from the study are presented in Table 3 and Table 4. Wheat yield was projected to remain above baseline (1970-2000) levels until 2080 but may decrease somewhat by 2080 relative to 2050. Rice yield was projected to steadily increase over time, whereas maize showed a steadily increasing yield deficit relative to the baseline scenario over time.

Scenario	Year	Wheat	Rice	Maize
A1FI	2020	2.67	0.54	-0.33
	2050	6.29	6.05	-0.71
	2080	-0.44	8.95	-10.44
A2a	2020	1.49	0.60	-1.51
	2050	10.22	4.34	3.22
	2080	8.52	10.65	-2.48
A2b	2020	3.10	0.07	0.10
	2050	7.29	4.42	0.29
	2080	5.39	11.44	-5.61
A2c	2020	4.99	0.44	1.99
	2050	8.33	4.99	1.33
	2080	7.05	10.74	-3.95
B1a	2020	-0.24	-0.17	-3.24
	2050	3.46	2.20	-1.54
	2080	4.16	1.16	-1.84
B2a	2020	5.60	-0.23	2.60
	2050	3.31	2.40	-1.69
	2080	5.54	5.73	-1.46
B2b	2020	1.26	-0.56	-1.74
	2050	0.43	2.36	-4.57
	2080	4.86	5.70	-2.14

Table 3. Wheat, rice and maize yield changes (%) relative to baseline scenario (1970-2000) for Australia, for different emission scenarios and future time periods. Some emissions scenarios were run in an ensemble simulation (e.g. A2a, A2b, A2c). Data is from Iglesias and Rosenzweig (2009).

	Wheat		Rice		Maize	
	Up	Down	Up	Down	Up	Down
Baseline to 2020	6	1	4	3	3	4
Baseline to 2050	7	0	7	0	3	4
Baseline to 2080	6	1	7	0	0	7
2020 to 2050	5	2	7	0	3	4
2050 to 2080	3	4	6	1	2	5

Table 4. The number of emission scenarios that predict yield gains ("Up") or yield losses ("Down") for wheat, rice and maize between two points in time for Australia. Data is from Iglesias and Rosenzweig (2009).

Elsewhere, recent studies have assessed the impact of climate change on a global-scale and include impact estimates for Oceania as a whole (Fischer, 2009, Tatsumi et al., 2011). Whilst these studies provide a useful indicator of crop yields under climate change for the region, it should be noted that the crop yields presented in such cases are not definitive national estimates. This is because the yields are averaged over the entire region, which includes other countries as well as Australia.

Fischer (2009) projected global 'production potential' changes for 2050 using the GAEZ (Global Agro-Ecological Zones) crops model with climate change scenarios from the

HadCM3 and CSIRO GCMs respectively, under SRES A2 emissions. The impact of future climate on crop yields of rain-fed cereals are presented in Table 5 (relative to yield realised under current climate) for Oceania and Polynesia.

	CO ₂ fert.	2020s		2050s		2080s	
		CSIRO	HADCM3	CSIRO	HADCM3	CSIRO	HADCM3
Rain-fed wheat	Yes	4	-8	11	18	4	9
	No	2	n/a ¹	6	n/a	-4	n/a
Rain-fed maize	Yes	19	12	31	34	57	58
	No	17	n/a	27	n/a	50	n/a
Rain-fed cereals	Yes	n/a	-7	n/a	8	n/a	2
	No	n/a	n/a	n/a	n/a	n/a	n/a
Rain-fed sorghum	Yes	4	n/a	9	n/a	7	n/a
	No	2	n/a	6	n/a	3	n/a

Table 5. Impacts of climate change on the production potential of rain-fed cereals in current cultivated land (% change with respect to yield realised under current climate), with two GCMs and with and without CO₂ fertilisation (“CO₂ fert.”) under SRES A2 emissions. Data is from Fischer (2009).

Tatsumi et al. (2011) applied an improved version of the GAEZ crop model (iGAEZ) to simulate crop yields on a global scale for wheat, potato, cassava, soybean, rice, sweet potato, maize, green beans. The impact of global warming on crop yields from the 1990s to 2090s was assessed by projecting five GCM outputs under the SRES A1B scenario and comparing the results for crop yields as calculated using the iGAEZ model for the period of 1990-1999. The results for Oceania are displayed in Table 6.

Wheat	Potato	Cassava	Soybean	Rice	Sweet potato	Maize	Green beans
3.81	-3.82	-	8.67	8.79	1.79	-0.66	1.63

Table 6. Average change in yield (%), during 1990s-2090s in Oceania. Data is from Tatsumi et al. (2011).

In addition to the studies looking at the effect of changes in climate and CO₂ concentrations on crop yield Avnery et al. (2011) investigated the effects of ozone surface exposure on crop yield losses for soybeans, maize and wheat under the SRES A2 and B1 scenarios respectively. Two metrics of ozone (O₃) exposure were investigated; seasonal daytime (08:00-19:59) mean O₃ (“M12”) and accumulated O₃ above a threshold of 40 ppbv (“AOT40”). The results for Australia are presented in Table 7.

	A2		B1	
	M12	AOT40	M12	AOT40
Soybeans	4-6	0-2	2-4	0-2
Maize	0-2	0-2	0-2	0-2
Wheat	0-2	0-2	0-2	0-2

Table 7. National relative crop yield losses (%) for 2030 under A2 and B1 emission scenarios according to the M12 (seasonal daytime (08:00–19:59) mean) and AOT40 (accumulated O₃ above a threshold of 40 ppbv) metrics of O₃ exposure. Data is from Avnery et al. (2011).

National-scale or sub-national scale assessments

Climate change studies

Included in this section are results from recent studies that have applied crop models, alongside meteorological models and information for global climate models, to produce national or sub-national scale projections of future crop yields in Australia.

Anwar et al. (2007) applied climate projections from the CCAM (Mark2) and CCAM (Mark3) GCMs respectively, under A1FI, A2, and B2 emissions scenarios to the CropSyst (v4) crop model to estimate the impact of climate change on wheat yield at Birchip, a location in south-eastern Australia. The study found a strong and consistent positive trend in mean diurnal temperature range and a significant negative trend in wheat yield under the three emissions scenarios with and without elevated CO₂ concentration. Across present climate to projected high (A1FI), mid (A2) and low (B2) global warming scenarios in 2070, median wheat yield in the absence of the CO₂ fertiliser effect decreased by about 29%. Under the same climate scenarios, but with an elevated atmospheric CO₂ climate, median wheat yield decreased by about 25%. Anwar et al. (2007) note that negative trends identified over the future decades may be artefacts of the method of substituting historical variance for future variance, so the results should be treated with caution.

O’Leary et al. (2010) demonstrated sub-regional variability in simulated wheat yields across Victoria, Australia, under climate change. The authors showed that under the A1FI scenario, reduced rainfall in north-western Victoria is a major challenge with significant wheat yield losses (-10 to -20%) estimated for 2050, if crops are sown outside the June sowing window. For the high rainfall zone in the South West, yield gains (+10 to +20%) were projected for 2050. O’Leary et al. (2010) conclude that despite the greater uncertainty in climate models compared to crop models, in the context of a moderate global average temperature rise of about 2°C, they expect that wheat crop phenological development can be re-engineered

towards slower-developing spring types and that growers will need to alter sowing times to maximise grain yield under future climate scenarios across Victoria.

Within the Garnaut Climate Change Review, Crimp et al. (2008) developed general response functions to express wheat yield as a function of likely future climatic conditions, i.e. ranges of CO₂ (350-750 ppm), temperature (0-4 °C) and rainfall (-30% to 20%) for 10 sites spanning Australia's southern wheat belt. Increasing CO₂ conditions *alone* were associated with increases in yield relative to historic mean (1957-2006) of 18-36%. Modifying the planting window to take advantage of a reduction in the duration of the annual frost period delivered additional yield gains.

Australia's rice growing regions are located in the south-east of the country, around the Murray River and the Murrumbidgee River in the Murray Valley and Murrumbidgee Irrigation Areas. Gaydon et al. (2010) notes that availability of water could decline both as a result of climate change as well as policies to increase environmental flows in this area, which would have major negative impact on rice yields in Australia, because of a total dependence on irrigation. CO₂ fertilisation could offset some of the rice yield losses but the effects of CO₂ fertilisation in Australia are largely un-researched, according to Gaydon et al. (2010). The rice industry has successfully increased water efficiency throughout its history, and it will need to continue to do so, in order to cope with future climate change (Gaydon et al., 2010).

A useful review of the impact of climate change on wine grapes in Australia is presented by Webb et al. (2010). The review reports that a warmer climate could result in ripening earlier in the season, which is likely to compress the harvesting and processing period (Webb et al., 2011b). Moreover, the quality of existing mainstream wine grape varieties could be reduced if no adaptation strategies are implemented. To this end, Webb et al. (2010) note that consumer education relating to new wine styles and varieties could be important, since the typical wine style of a given region is likely to change. Furthermore, varieties presently grown could be replaced with 'later season' varieties to compensate for warmer temperatures and later seasons (Webb et al., 2011a).

The above national-scale studies point towards a need for adaptation to climate change in the agricultural sector. Various adaptation options are discussed in detail by Howden et al. (2010). Many of the adaptations required are extensions of those currently used for managing climate variability in Australia, e.g. technical adaptations such as changed crop management practices, new varieties, altered rotations and improved water management. However, Howden et al. (2010) notes that these practices may need to be modified,

enhanced or integrated in different ways, in order to be able to deal appropriately with future climate change.

AVOID programme results

To further quantify the impact of climate change on crops, the AVOID programme simulated the effect of climate change on the suitability of land for crop cultivation for all countries reviewed in this literature assessment based upon the patterns of climate change from 21 GCMs (Warren et al., 2010). This ensures a consistent methodological approach across all countries and takes consideration of climate modelling uncertainties.

Methodology

The effect of climate change on the suitability of land for crop cultivation is characterised here by an index which defines the percentage of cropland in a region with 1) a decrease in suitability or 2) an increase in suitability. A threshold change of 5% is applied here to characterise decrease or increase in suitability. The crop suitability index is calculated at a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$, and is based on climate and soil properties in Ramankutty et al. (2002). The baseline crop suitability index, against which the future changes are measured, is representative of conditions circa 2000. The key features of the climate for the crop suitability index are temperature and the availability of water for plants. Changes in these were derived from climate model projections of future changes in temperature and precipitation, with some further calculations then being used to estimate actual and potential evapotranspiration as an indicator of water availability. It should be noted that changes in atmospheric CO₂ concentrations can decrease evapotranspiration by increasing the efficiency of water use by plants Ramankutty et al. (2002), but that aspect of the index was not included in the analysis here. Increased CO₂ can also increase photosynthesis and improve yield to a small extent, but again these effects are not included. Exclusion of these effects may lead to an overestimate of decreases in suitability.

The index here is calculated only for grid cells which currently contain cropland, as defined in the global crop extent data set described by Ramankutty et al. (2008). It is assumed that crop extent does not change over time. The crop suitability index varies significantly for current croplands across the world (Ramankutty et al., 2002), with the suitability being low in some current cropland areas according to this index. Therefore, while climate change clearly has the potential to decrease suitability for cultivation if temperature and precipitation regimes become less favourable, there is also scope for climate change to increase suitability in some existing cropland areas if conditions become more favourable in areas

where the suitability index is not at its maximum value of 1. It should be noted that some areas which are not currently croplands may already be suitable for cultivation or may become suitable as a result of future climate change, and may become used as croplands in the future either as part of climate change adaptation or changes in land use arising for other reasons. Such areas are not included in this analysis.

Results

Crop suitability was estimated under the pattern of climate change from 21 GCMs with two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation policy where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate modelling, although it is acknowledged that only one crop suitability impacts model is applied. Simulations were performed for the years 2030, 2050, 2080 and 2100. The results for Australia are presented in Figure 2.

Under both the climate projections, some existing cropland areas become less suitable for cultivation while none are projected to become more suitable, with the exception of three models. The areas of declining suitability differ according to the climate model used, and these differences themselves change over time.

In 2030, the proportion of Australian croplands becoming less suitable ranges from 30% to 95% under both the A1B and mitigation scenarios, including the outlier models. Further into the 21st century, the range including the outlier models remains similar to that of the 2030s for both scenarios, although the full distributions of results change, with more of the models projecting larger areas of cropland with declining suitability. The consensus between models on large areas of declining suitability becomes stronger under the A1B scenario than for the mitigation scenario. By 2100, all except 3 models under A1B imply that between 90% and 100% of Australian croplands are less suitable, but under the mitigation scenario a quarter of the models project smaller areas of declining suitability – 80% or lower.

So, for Australia, while the possibility exists that nearly all croplands could experience an early and sustained decline in suitability even under the mitigation scenario, the models give a range of results early in the 21st century and this uncertainty remains through the century in the mitigation scenario.

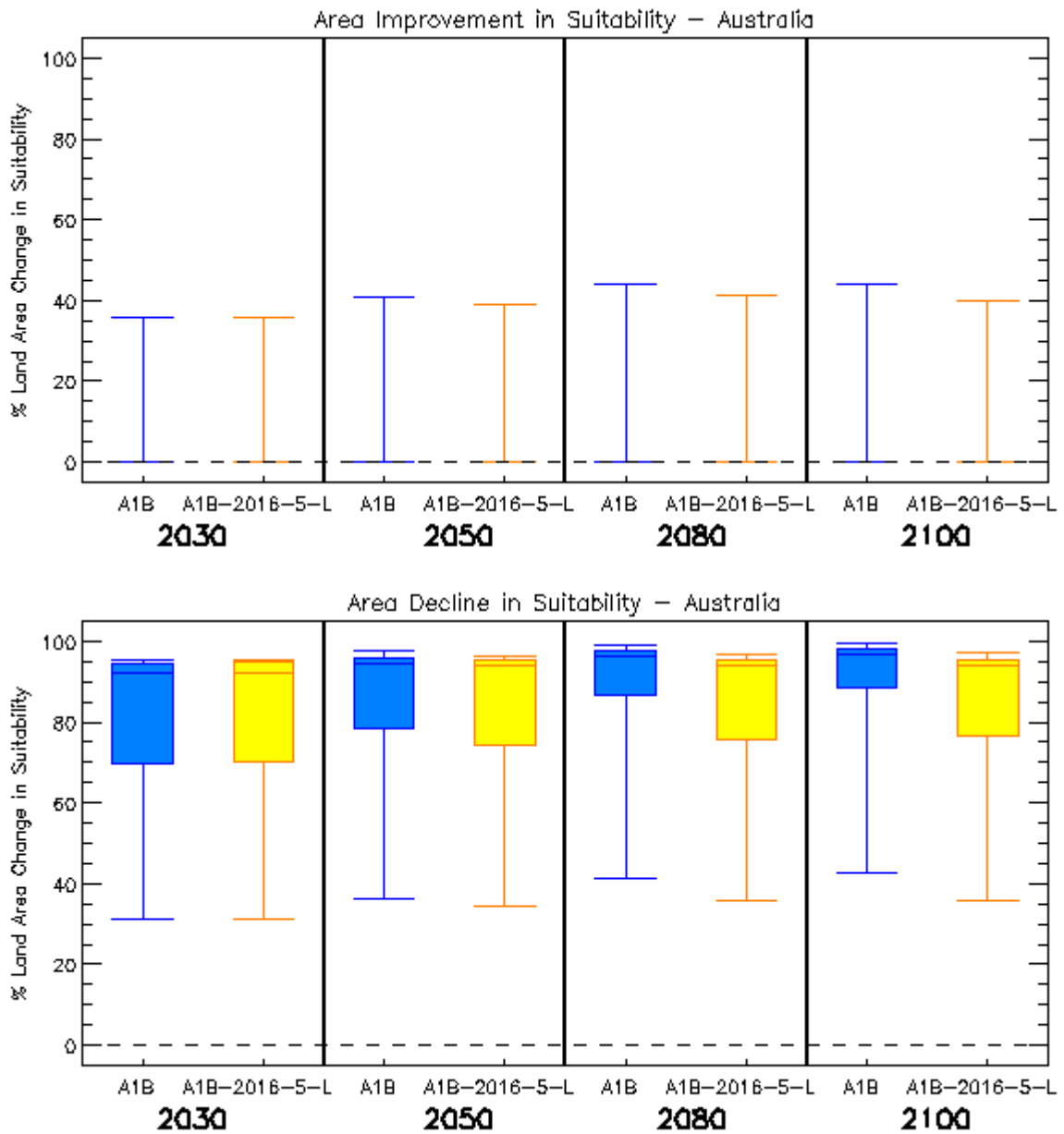


Figure 2. Box and whisker plots for the impact of climate change on increased crop suitability (top panel) and decreased crop suitability (bottom panel) for Australia, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).

Food security

Headline

Recent assessments are in agreement that Australia could remain food-secure with climate change and that a small increase (~3%) in maximum fish catch potential may be possible by the 2050s under SRES A1B scenario.

Supporting literature

Introduction

Food security is a concept that encompasses more than just crop production, but is a complex interaction between food availability and socio-economic, policy and health factors that influence access to food, utilisation and stability of food supplies. In 1996 the World Food Summit defined food security as existing 'when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs, and their food preferences are met for an active and healthy life'.

As such this section cannot be a comprehensive analysis of all the factors that are important in determining food security, but does attempt to assess a selection of the available literature on how climate change, combined with projections of global and regional population and policy responses, may influence food security.

Assessments that include a global or regional perspective

Climate change studies Australia is not a country of high concern in terms of food security, particularly in a global context. According to FAO statistics Australia has an extremely low level of undernourishment, (less than 5% of the population). Moreover, a number of global studies point towards a generally optimistic and positive outlook for the impact of climate change on food security in Australia.

The most recent of these is presented by Wu et al. (2011). Crop yields were simulated by the GIS-based Environmental Policy Integrated Climate (EPIC) model. This was combined with crop areas simulated by a crop choice decision model to calculate total food production and per capita food availability across the globe, which was used to represent the status of food availability and stability. The study focussed on the SRES A1 scenario and applied climate change simulations for the 2000s (1991–2000) and 2020s (2011–2020). The climate simulations were performed by MIROC (Model for Interdisciplinary Research on Climate)

version 3.2., which means the effects of climate model uncertainty were not considered. Downscaled population and GDP data from the International Institute for Applied Systems Analysis (IIASA) were applied in the simulations. Wu et al. (2011) conclude that whilst coastal south-eastern and south-western Australia tend to be hot spots for food security vulnerability between 2000 and 2020, Australia's population may still be food-secure as their population does not rely strongly on subsistence agriculture. Also, Australia possesses a high capability for importing food due to strong purchasing power and financial support, as well as substantial adaptive capacity and proactive food management systems.

A further study by Falkenmark et al. (2009) present a global analysis of food security under climate change scenarios for the 2050s that considers the importance of water availability for ensuring global food security. The study presents an analysis of water constraints and opportunities for global food production on current croplands and assesses five main factors:

- 1) how far improved land and water management might go towards achieving global food security,
- 2) the water deficits that would remain in regions currently experiencing water scarcity and which are aiming at food self-sufficiency,
- 3) how the water deficits above may be met by importing food,
- 4) the cropland expansion required in low income countries without the needed purchasing power for such imports, and
- 5) the proportion of that expansion pressure which will remain unresolved due to potential lack of accessible land.

Similar to the study presented by Wu et al. (2011), there is no major treatment of modelling uncertainty; simulations were generated by only the LPJml dynamic global vegetation and water balance model Gerten et al. (2004) with population growth and climate change under the SRES A2 emission scenario. Falkenmark et al. (2009) summarise the impacts of future improvements (or lack thereof) in water productivity for each country across the globe and show that this generates either a deficit or a surplus of water in relation to food water requirements in each country. These can be met either by trade or by horizontal expansion (by converting other terrestrial ecosystems to crop land). The study estimated that in 2050 around one third of the world's population will live in each of three regions: those that export food, those that import food, and those that have to expand their croplands at the expense of

other ecosystems because they do not have enough purchasing power to import their food. The simulations demonstrated that Australia could be a food exporting country in 2050.

The International Food Policy Research Institute (IFPRI) have produced a report and online tool that describes the possible impact of climate change on two major indicators of food security; 1) the number of children aged 0-5 malnourished, and 2) the average daily kilocalorie availability (Nelson et al., 2010, IFPRI, 2010). The study considered three broad socio-economic scenarios; 1) a 'pessimistic' scenario, which is representative of the lowest of the four GDP growth rate scenarios from the Millennium Ecosystem Assessment GDP scenarios and equivalent to the UN high variant of future population change, 2) a 'baseline' scenario, which is based on future GDP rates estimated by the World Bank and a population change scenario equivalent to the UN medium variant, and 3) an 'optimistic' scenario that is representative of the highest of the four GDP growth rate scenarios from the Millennium Ecosystem Assessment GDP scenarios and equivalent to the UN low variant of future population change. Nelson et al. (2010) also considered climate modelling and emission uncertainty and included a factor to account for CO₂ fertilisation in their work. The study applied two GCMs, the CSIRO GCM and the MIROC GCM, and forced each GCM with two SRES emissions scenarios (A1B and B1). They also considered a no climate change emissions scenario, which they called 'perfect mitigation' (note that in most other climate change impact studies that this is referred to as the baseline). The perfect mitigation scenario is useful to compare the effect of climate change against what might have happened without, but is not a realistic scenario itself. IFPRI have not published projections for child malnourishment in Australia but information on average daily kilocalorie availability has been made available. Table 8 displays the average daily kilocalorie availability simulated under different climate and socioeconomic scenarios for Australia and Figure 3 displays the effect of climate change, calculated by comparing the 'perfect mitigation' scenario with each baseline, optimistic and pessimistic scenario. By 2050, climate change is attributable for up to a 6% decline in average kilocalorie availability. Figure 4 shows how the changes projected for Argentina compare with the projections for the rest of the globe (IFPRI, 2010).

Scenario	2010	2050
Baseline CSI A1B	2994	2981
Baseline CSI B1	2997	2998
Baseline MIR A1B	2982	2931
Baseline MIR B1	2990	2968
Baseline Perfect Mitigation	3024	3116
Pessimistic CSI A1B	3017	2783
Pessimistic CSI B1	3020	2798
Pessimistic MIR A1B	3005	2735
Pessimistic MIR B1	3010	2759
Pessimistic Perfect Mitigation	3048	2906
Optimistic CSI A1B	2993	3149
Optimistic CSI B1	2996	3162
Optimistic MIR A1B	2981	3091
Optimistic MIR B1	2986	3116
Optimistic Perfect Mitigation	3023	3288

Table 8. Average daily kilocalorie availability simulated under different climate and socioeconomic scenarios, for Australia (IFPRI, 2010).

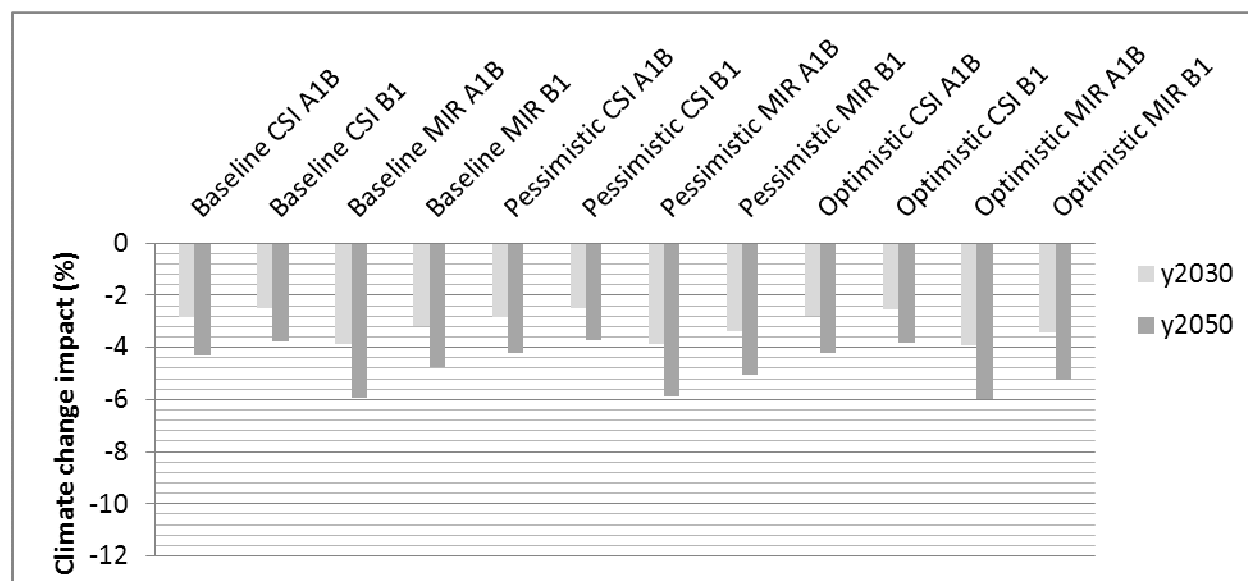


Figure 3. The impact of climate change on average daily kilocalorie availability for Australia (IFPRI, 2010).

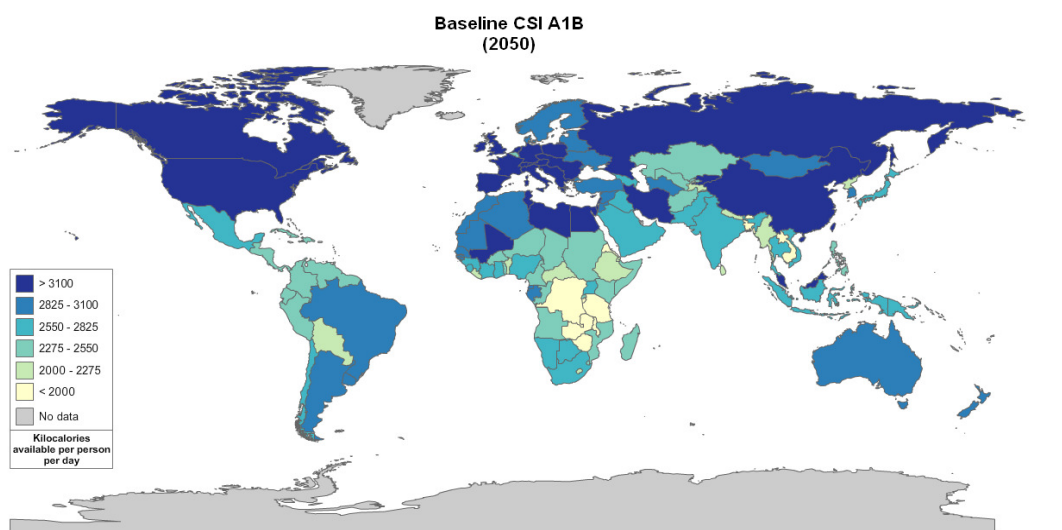
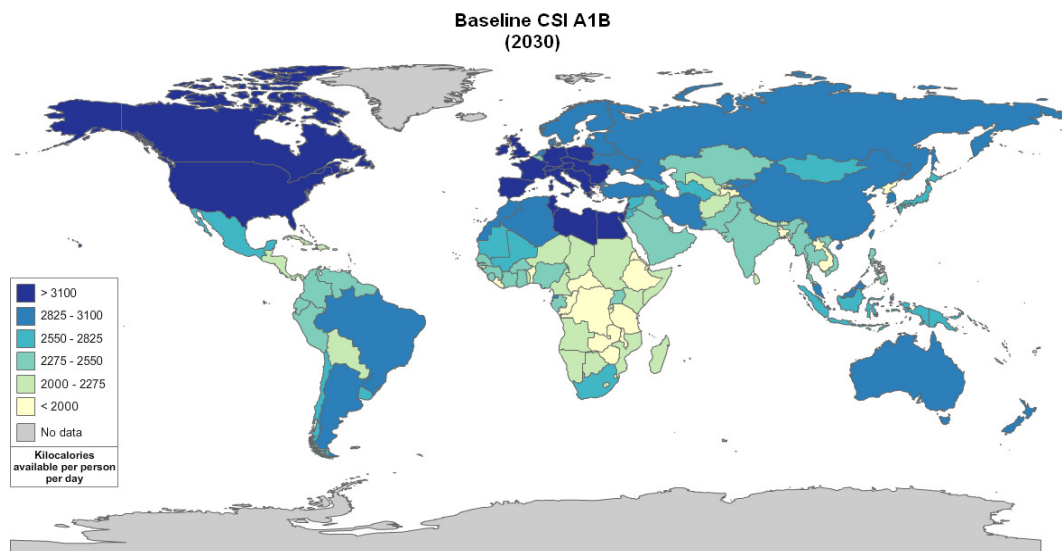
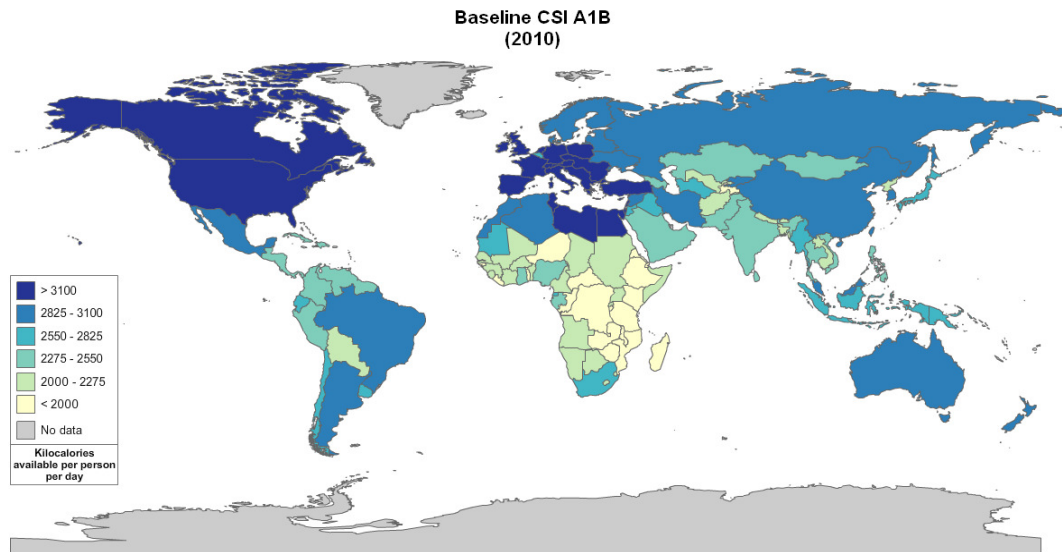


Figure 4. Average daily kilocalorie availability simulated by the CSIRO GCM (CSI) under an A1B emissions scenario and the baseline socioeconomic scenario (IFPRI, 2010), for 2010 (top panel), 2030 (middle panel) and 2050 (bottom panel) (IFPRI, 2010). The changes shown are the combination of both climate change and socio-economic changes.

It is important to note that up until recently, projections of climate change impacts on global food supply have tended to focus solely on production from terrestrial biomes, with the large contribution of animal protein from marine capture fisheries often ignored. However, recent studies have addressed this knowledge gap (Allison et al. 2009, Cheung et al., 2010). In addition to the direct affects of climate change, changes in the acidity of the oceans, due to increases in CO₂ levels, could also have an impact of marine ecosystems, which could also affect fish stocks. However, this relationship is complex and not well understood, and studies today have not been able to begin to quantify the impact of ocean acidification on fish stocks. Allison et al. (2009) present a global analysis that compares the vulnerability of 132 national economies to potential climate change impacts on their capture fisheries. The study considered a country's vulnerability to be a function of the combined effect of projected climate change, the relative importance of fisheries to national economies and diets, and the national societal capacity to adapt to potential impacts and opportunities. Climate change projections from a single GCM under two emissions scenarios (SRES A1FI and B2) were used in the analysis. Allison et al. (2009) concluded that the national economy of Australia presented a very low vulnerability to climate change impacts on fisheries. The adaptive capacity is also considered to be high for Australian fisheries and aquaculture businesses (Hobday et al., 2008). In contrast, countries in Central and Western Africa (e.g. Malawi, Guinea, Senegal, and Uganda), Peru and Colombia in north-western South America, and four tropical Asian countries (Bangladesh, Cambodia, Pakistan, and Yemen) were identified as most vulnerable (see Figure 5). It should be noted, however, that results from studies that have applied only a single climate model or climate change scenario should be interpreted with caution. This is because they do not consider other possible climate change scenarios which could result in a different impact outcome, in terms of magnitude and in some cases sign of change.

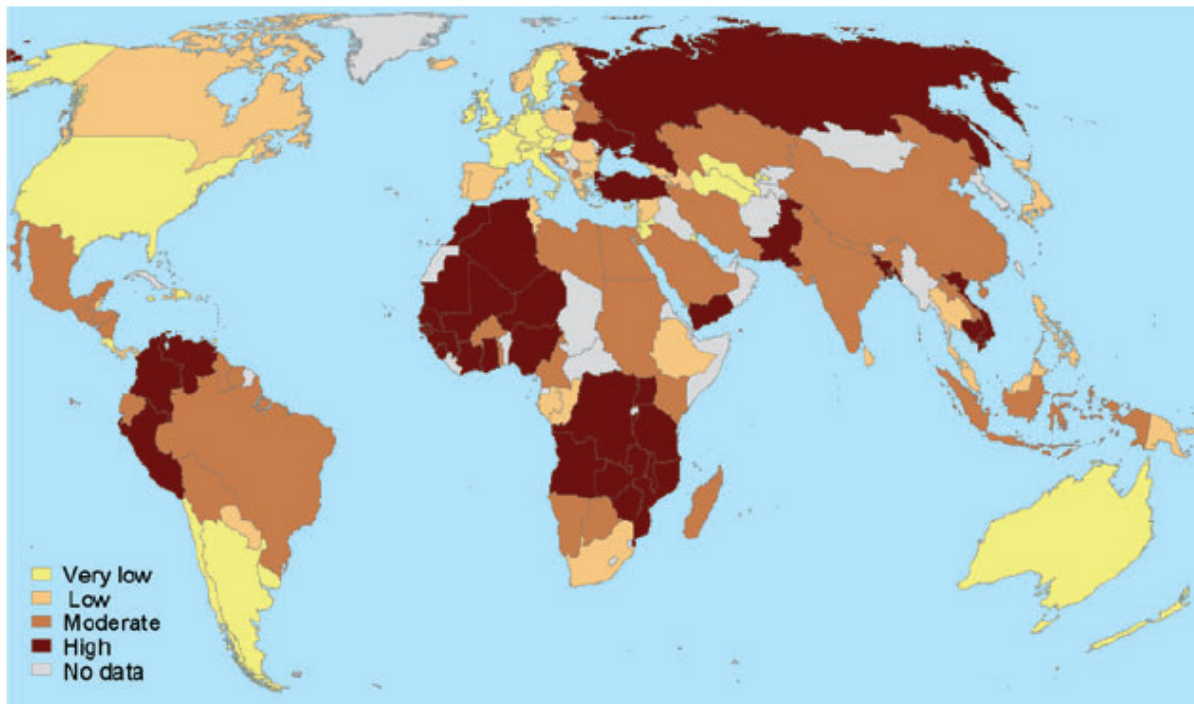


Figure 5 Vulnerability of national economies of potential climate change impacts on fisheries (which integrates exposure, sensitivity and adaptive capacity) under IPCC scenario B2 (local development, lower emissions). Colours represent quartiles with dark brown for the upper quartile (highest index value), yellow for the lowest quartile, and grey where no data were available.

Figure 5. Vulnerability of national economies to potential climate change impacts on fisheries under SRES B2 (Allison et al., 2009). Colours represent quartiles with dark brown for the upper quartile (highest index value), yellow for the lowest quartile, and grey where no data were available.

Cheung et al. (2010) also consider marine capture fisheries at the global scale for several countries. The study projected changes in global catch potential for 1066 species of exploited marine fish and invertebrates from 2005 to 2055 under climate change scenarios. Cheung et al. (2010) found that climate change may lead to large-scale redistribution of global catch potential, with an average of 30–70% increase in high-latitude regions and a decline of up to 40% in the tropics. The simulations were based climate simulations from a single GCM (GFDL CM2.1) under a SRES A1B emissions scenario (CO₂ concentration at 720ppm in 2100) and a stable-2000 level scenario (CO₂ concentration maintains at year 2000 level of 365 ppm). The limitations of applying a single GCM have been noted previously. For Australia, the projected change in the 10-year averaged maximum catch potential from 2005 to 2055 was around a 3% increase under A1B but a 7% reduction under the stabilisation scenario, based upon 74 exploited species included in the analysis. Figure 6 demonstrates how this compares with projected changes for other countries across the globe.

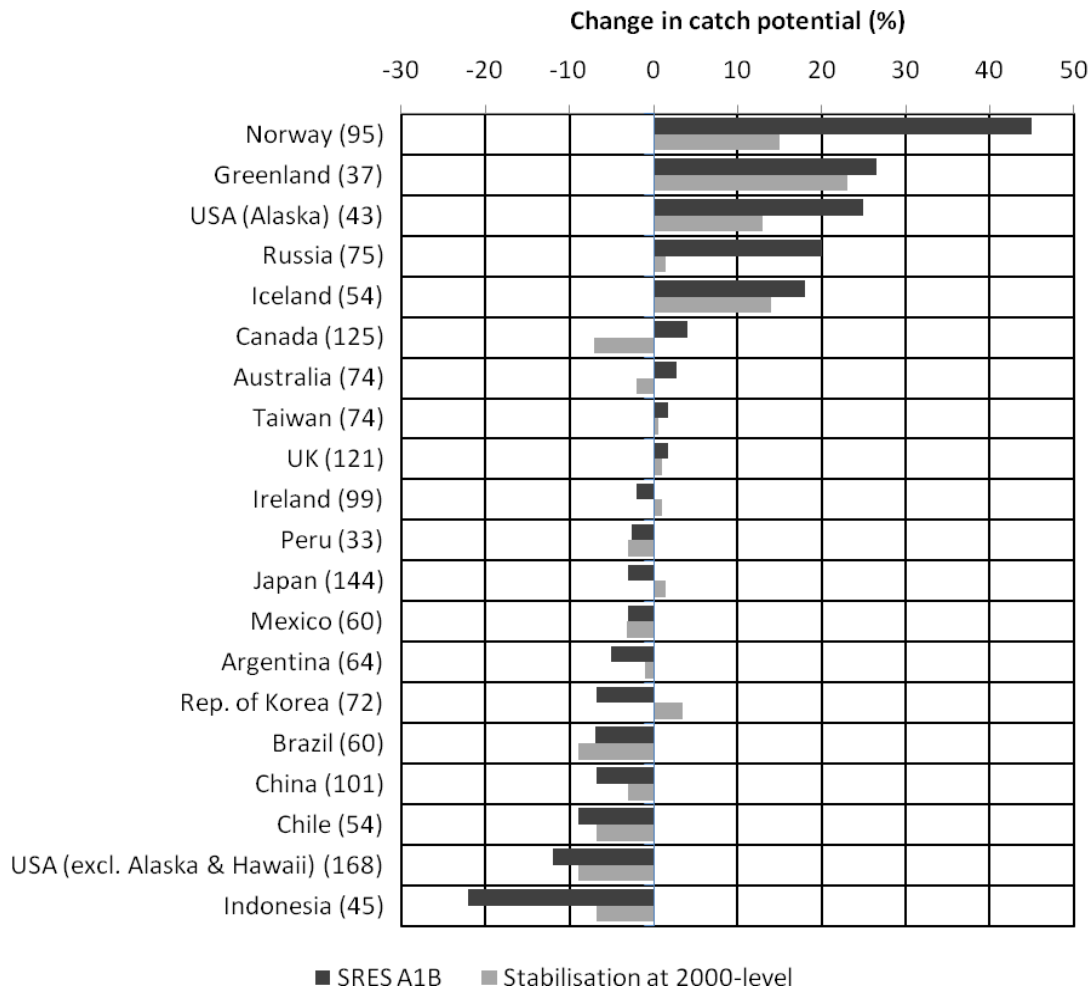


Figure 6. Projected changes in the 10-year averaged maximum catch potential from 2005 to 2055. The numbers in parentheses represent the numbers of exploited species included in the analysis. Adapted from Cheung et al. (2010).

National-scale or sub-national scale assessments

Climate change studies

Edwards et al. (2010) notes that Australian fisheries are worth more than AUD2.1 billion annually. Australians consume around 16kg of seafood per capita each year. However, the wild catches of almost all fish species have declined with some species, such as prawns, for a variety of reasons, and are now at only half the level of ten years ago. Importantly, Australia has now moved from a net exporter of fish to a net importer (Edwards et al., 2010). This suggests that while the possible adverse impacts due to climate change (under stabilisation only) presented by the global-scale assessment by Cheung et al. (2010), for Australia are relatively small, there could still be a discernible effect on the country's fisheries industry in economic terms. However, the other scenario that Cheung et al. (2010) considered, showed an increase in catch potential. Similarly, Brown et al. (2010) showed that under a plausible climate change scenario, primary production could increase around

Australia, which would generally benefit fisheries catch and value. However, Hobday and Poloczanska (2010) note a need for focussed regional studies that explore the relationship between climate variables and the various species of interest to Australian fisheries, in order to improve understanding of the possible impacts of climate change.

Water stress and drought

Headline

There is a high degree of uncertainty regarding how water availability in Australia could be affected by climate change, partly due to different GCMs simulating changes of different sign with climate change, but also due to studies considering different indicators of water stress. However, there is some consensus that south-eastern Australia could become drier with climate change and that as a result, water stress could increase in this region - this could be exacerbated by increasing population pressures.

Results from the AVOID programme for Australia are slightly different from the existing literature, indicating that Australia's population is not found to exhibit an increase or decrease in exposure to water stress with climate change.

Supporting literature

Introduction

For the purposes of this report droughts are considered to be extreme events at the lower bound of climate variability; episodes of prolonged absence or marked deficiency of precipitation. Water stress is considered as the situation where water stores and fluxes (e.g. groundwater and river discharge) are not replenished at a sufficient rate to adequately meet water demand and consumption.

A number of impact model studies looking at water stress and drought for the present (recent past) and future (climate change scenario) have been conducted. These studies are conducted at global or national scale and include the application of global water 'availability' or 'stress' models driven by one or more climate change scenario from one or more GCM. The approaches variously include other factors and assumptions that might affect water availability, such as the impact of changing demographics and infrastructure investment, etc. These different models (hydrological and climate), assumptions and emissions scenarios mean that there are a range of water stress projections for Australia. This section summarises findings from these studies to inform and contextualise the analysis performed by the AVOID programme for this project. The results from the AVOID work are discussed in the next section.

Important knowledge gaps and key uncertainties which are applicable to Australia as well as at the global-scale, include; the appropriate coupling of surface water and groundwater in hydrological models, including the recharge process, improved soil moisture and evaporation dynamics, inclusion of water quality, inclusion of water management (Wood et al. 2011) and further refinement of the down-scaling methodologies used for the climate driving variables (Harding et al. 2011).

Assessments that include a global or regional perspective

Recent past

Recent research presented by Vörösmarty et al. (2010) describes the calculation of an 'Adjusted Human Water Security Threat' (HWS) indicator. The indicator is a function of the cumulative impacts of 23 biophysical and chemical drivers simulated globally across 46,517 grid cells representing 99.2 million km². With a digital terrain model at its base, the calculations in each of the grid boxes of this model take account of the multiple pressures on the environment, and the way these combine with each other, as water flows in river basins. The level of investment in water infrastructure is also considered. This infrastructure measure (the *investment benefits factor*) is based on actual existing built infrastructure, rather than on the financial value of investments made in the water sector, which is a very unreliable and incomplete dataset. The analysis described by Vörösmarty et al. (2010) represents the current state-of-the-art in applied policy-focussed water resource assessment. In this measure of water security, the method reveals those areas where this is lacking, which is a representation of human water stress. One drawback of this method is that no analysis is provided in places where there is 'no appreciable flow', where rivers do not flow, or only do so for such short periods that they cannot be reliably measured. This method also does not address places where water supplies depend wholly on groundwater or desalination, being piped in, or based on wastewater reuse. It is based on what is known from all verified peer reviewed sources about surface water resources as generated by natural ecosystem processes and modified by river and other hydraulic infrastructure; i.e. not a mixture of natural and other (e.g. desalinisation) water supply (Vörösmarty et al., 2010).

Here, the present day HWS is mapped for Australia. The model applied operates at 50km resolution, so, larger countries appear to have smoother coverage than smaller countries, but all are mapped and calculated on the same scale, with the same data and model, and thus comparisons between places are legitimate. It is important to note that this analysis is a comparative one, where each place is assessed *relative* to the rest of the globe. In this way, this presents a realistic comparison of conditions across the globe. As a result of this, however, some places may seem to be less stressed than may be originally considered. An

important example is Australia, which is noted for its droughts and long dry spells, and while there are some densely populated cities in that country where water stress is a real issue (many Australian cities experienced water stress and had to impose water restrictions during the recent prolonged drought from 2007-2009), for most of the country, *relative to the rest of the world*, the measure suggests water stress (as measured by HWS defined by Vörösmarty et al. (2010)), is not a serious problem (see Figure 7). The highest rainfall and river levels are in the northern parts of the country, along a small part of the central east coast, and within the Murray Darling Basin in the South. Large areas of the country have no appreciable flow, and just a few places experience water stress as a result of low rainfall, high levels of pollution or large levels of water withdrawal.

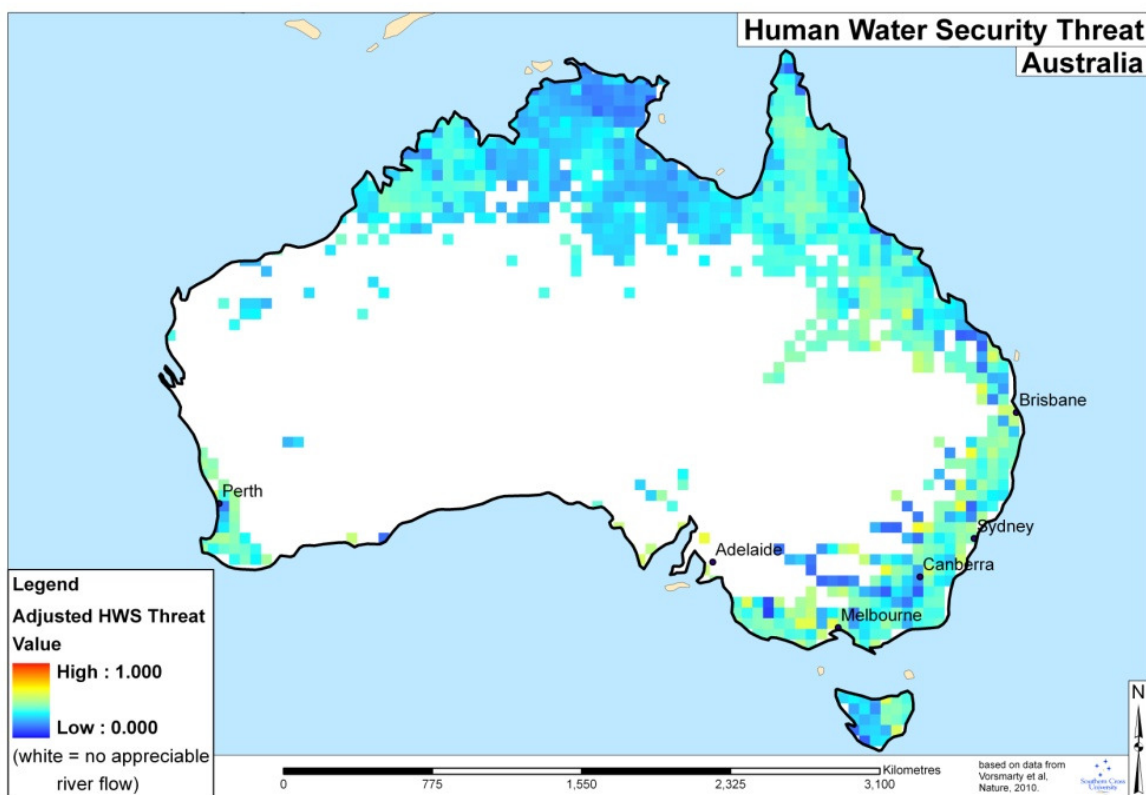


Figure 7. Present Adjusted Human Water Security Threat (HWS) for Australia, calculated following the method described by Vörösmarty et al. (2010).

Smakhtin et al. (2004) present a first attempt to estimate the volume of water required for the maintenance of freshwater-dependent ecosystems at the global scale. This total environmental water requirement (EWR) consists of ecologically relevant low-flow and high-flow components. The authors argue that the relationship between water availability, total use and the EWR may be described by the water stress indicator (WSI). If WSI exceeds 1.0, the basin is classified as “environmentally water scarce”. In such a basin, the discharge has already been reduced by total withdrawals to such levels that the amount of water left in the

basin is less than EWR. Smaller index values indicate progressively lower water resources exploitation and lower risk of “environmental water scarcity.” Basins where WSI is greater than 0.6 but less than 1.0 are arbitrarily defined as heavily exploited or “environmentally water stressed” and basins where WSI is greater than 0.3 but less than 0.6 are defined as moderately exploited. In these basins, 0-40% and 40-70% of the utilizable water respectively is still available before water withdrawals come in conflict with the EWR. Environmentally “safe” basins are defined as those where WSI is less than 0.3. The global distribution of WSI for the 1961-1990 time horizon is shown in Figure 8. The results show that for the basins considered, much of Australia presents a low WSI, apart from the south-east of the country where the WSI is high (in agreement with the results presented in Figure 7).

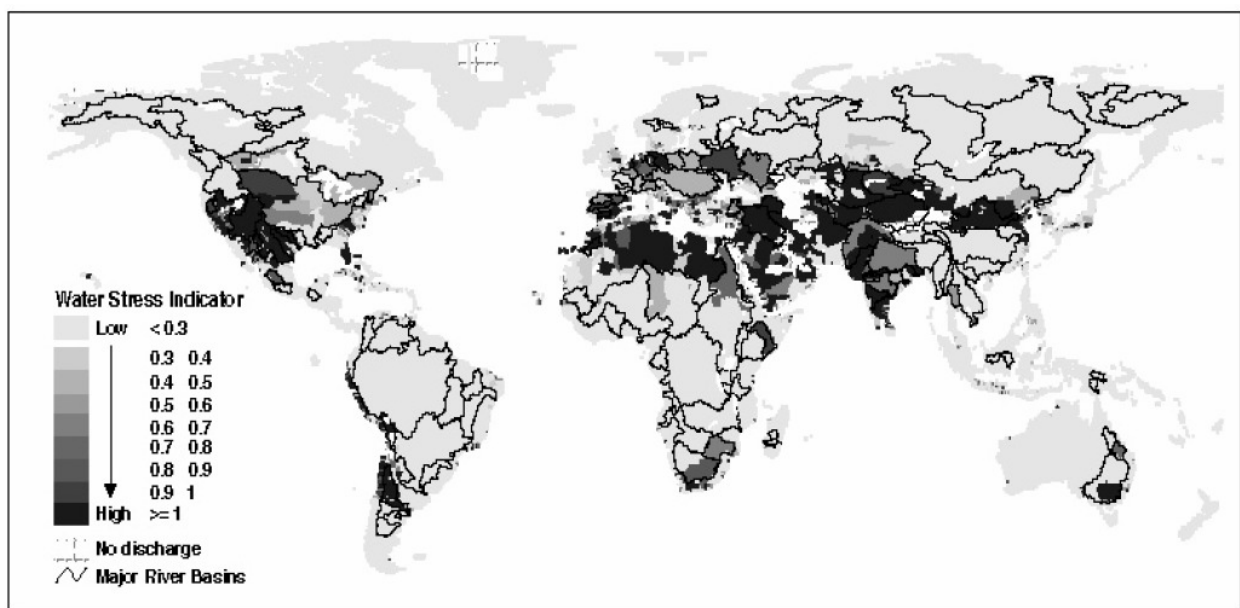


Figure 8. A map of the major river basins across the globe and the water stress indicator (WSI) for the 1961-1990 time horizon. The figure is from Smakhtin et al. (2004).

Climate change studies

The IPCC AR4 found that precipitation is likely to decrease in southern Australia in winter and spring, and very likely to decrease in south-western Australia during winter, with climate change (IPCC, 2007a). Changes in rainfall in northern and central Australia are uncertain. An increase in potential evaporation (PE) is likely, as is an increased risk of drought in southern Australia. Changes in PE have been calculated for a range of enhanced greenhouse gas model simulations, and in all cases increases in PE were simulated, and in most cases the moisture balance deficit became larger (IPCC, 2007a). This gives a strong indication that the Australian environment will become drier under enhanced greenhouse conditions. This is supported by more recent work presented by Washington et al. (2009). The authors investigated climate change projections from an aggressive mitigation scenario

(CO₂ stabilisation in 2100 at around 450ppm) compared with a non-mitigation scenario (CO₂ concentrations around 740ppm in 2100). For the 2080-2099 time horizon, they found that mitigation was associated with rainfall up to 20% less than no-mitigation, for northwest Australia, although precipitation increased from present for both scenarios. In south Australia, precipitation decreased under both scenarios and mitigation had little effect.

Rockstrom et al.(2009) applied the LPJml vegetation and water balance model (Gerten et al. 2004) to assess green-blue water (irrigation and infiltrated water) availability and requirements. The authors applied observed climate data from the CRU TS2.1 gridded dataset for a present-day simulation, and climate change projections from the HadCM2 GCM under the SRES A2 scenario to represent the climate change scenario for the year 2050. The study assumed that if water availability was less than 1,300m³/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The simulations presented by Rockstrom et al.(2009) should not be considered as definitive, however, because the study only applied one climate model, which means climate modelling uncertainty was overlooked. The results from the two simulations are presented in Figure 9. Rockstrom et al. (2009) found that globally in 2050 and under the SRES A2 scenario, around 59% of the world's population could be exposed to "blue water shortage" (i.e. irrigation water shortage), and 36% exposed to "green water shortages" (i.e. infiltrated rain shortage). For Australia, Rockstrom et al. (2009) found that blue-green water availability was well above the 1,300m³/capita/year threshold in present conditions and under climate change.

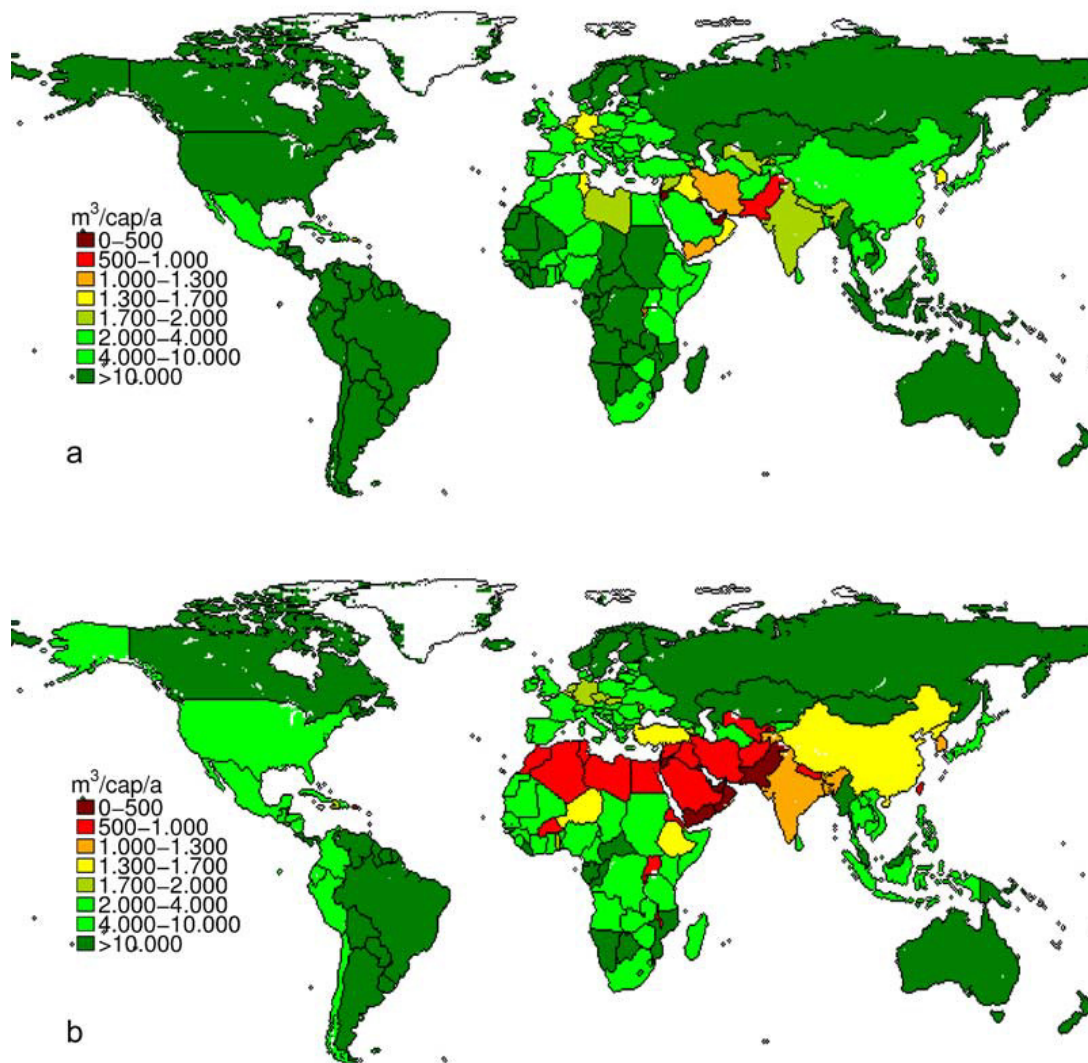


Figure 9. Simulated blue-green water availability ($m^3/\text{capita}/\text{year}$) for present climate (top panel) and including both demographic and climate change under the SRES A2 scenario in 2050 (bottom panel). The study assumed that if water availability was less than $1,300m^3/\text{capita}/\text{year}$, then the country was considered to present insufficient water for food self-sufficiency. The figure is from Rockstrom et al. (2009).

Doll (2009) presents updated estimates of the impact of climate change on groundwater resources by applying a new version of the WaterGAP hydrological model. The study accounted for the number of people affected by changes in groundwater resources under climate change relative to present (1961-1990). To this end, the study provides an assessment of the vulnerability of humans to decreases in available groundwater resources (GWR). This indicator was termed the “Vulnerability Index” (VI), defined as; $VI = -\% \text{ change GWR} * \text{Sensitivity Index (SI)}$. The SI component was a function of three more specific sensitivity indicators that include an indicator of water scarcity (calculated from the ratio between consumptive water use to low flows), an indicator for the dependence upon groundwater supplies, and an indicator for the adaptive capacity of the human system. Doll (2009) applied climate projections from two GCMs (ECHAM4 and HadCM3) to WaterGAP,

for two scenarios (SRES A2 and B2), for the 2050s. Figure 10 presents each of these four simulations respectively. There is variation across scenarios and GCMs. Western Australia is only predicted to be highly vulnerable to future decreases in available groundwater with the ECHAM4 simulations, while eastern Australia is only vulnerable under the HadCM3 projections. This implies a high degree of uncertainty in climate projections and resulting impacts on water stress for Australia.

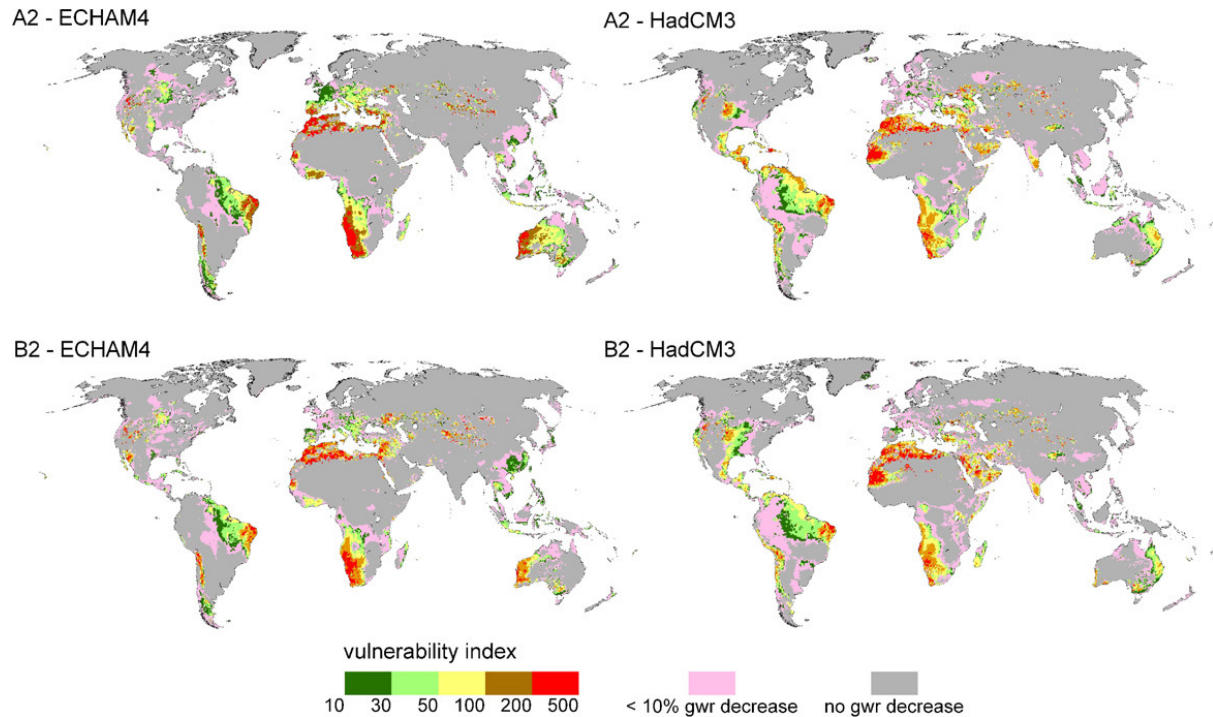


Figure 10. Vulnerability index (VI) showing human vulnerability to climate change induced decreases of renewable groundwater resources (GWR) by the 2050s under two emissions scenarios for two GCMs. VI is only defined for areas with a GWR decrease of at least 10% relative to present (1961-1990). The figure is from Doll (2009).

Fung et al. (2011) applied climate change scenarios for prescribed global-mean warming of 2°C and 4°C respectively, from two ensembles; 1) an ensemble of 1518 (2°C world) and 399 (4°C) members from the ClimatePrediction.net (CPDN) experiments, and 2) an ensemble of climate projections from 22 CMIP3 multi-model dataset GCMs. The climate projections were applied to the MacPDM global hydrological model (Gosling and Arnell, 2011) and population projections followed the UNPOP60 population scenario. Fung et al. (2011) calculated a water stress index (WSI) based upon resources per capita, similar to the method applied by Rockstrom et al. (2009). Results from the simulations are presented in Figure 11. There was consensus across models that water stress increases with climate change in south-eastern Australia. This high level of certainty is in contrast to the high level of uncertainty found for the same region by Doll (2009).

It should be noted that the estimates of drying across the globe that are presented by Fung et al. (2011) could be over-estimated slightly. This is because the MacPDM hydrological model is an offline model; i.e. it is not coupled to an ocean-atmosphere GCM. Therefore the dynamical effects of vegetation changes in response to water availability are not simulated. Recent work has highlighted that increased plant water use efficiency under higher CO₂ may ameliorate future increased drought to some extent, but not completely (Betts et al., 2007).

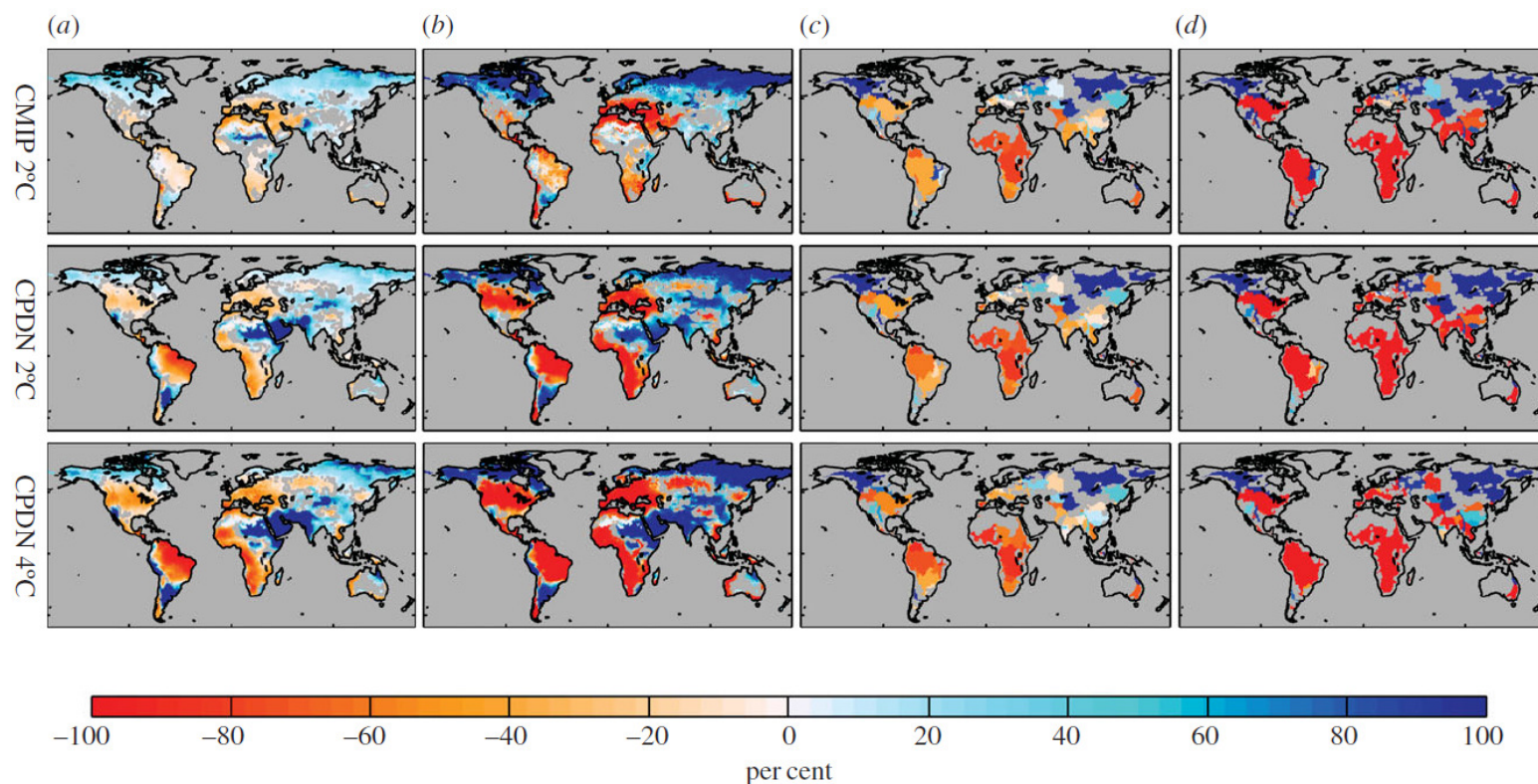


Figure 11. For a 2 °C and 4 °C rise in temperature and UNPOP60 population scenario compared with the baseline period (1961-1990); (a) spatial pattern of ensemble-average changes in mean annual run-off (DMAR), (b) model consensus on direction of change in run-off, (c) ensemble-average change in water stress (DWSI) and (d) model consensus on the direction of change in water stress. For the model consensus, red and therefore negative values represent the percentage of models showing a negative change in the respective parameter and blue, and therefore positive values represent the percentage of models showing a positive change. For DMAR and DWSI, colour classification spans from -100% to greater than 100% (this means that high positive values of DMAR and DWSI are effectively filtered out in these plots), whereas for consensus, colour classification spans from -100% to 100%. For plots of DMAR and consensus for the direction of change in run-off, grey land areas represent where DMAR is less than natural variability. For DWSI and consensus for direction of change in water stress, only 112 major river basins are plotted (Greenland has been excluded from the analysis). The figure is from Fung et al. (2011).

National-scale or sub-national scale assessments

Climate change studies

Whetton and Suppiah (2003) simulated monthly frequencies of serious rainfall deficiency in Victoria with climate change. The authors found a marked increase in the frequency of rainfall deficiencies in most simulations, with doubling in some cases by 2050. Cai et al. (2009) investigated a severe drought experienced across the southern Murray-Darling Basin in the past decade. Annual rises in temperature of 1 °C were found to drive a 9% reduction in soil moisture. The study found that since 1950, rising temperatures contributed to 45% of the total soil moisture reduction. The authors concluded that climate change will further exacerbate this problem, leading to more droughts and a requirement for increased irrigation demand to sustain regional agriculture. This could in turn lead to competing requirements with other users and increased water stress.

Vaze et al. (2011) applied climate projections from 15 GCMs under the A1B emissions scenario to drive two daily conceptual rainfall-runoff models (the SIMHYD and Sacramento models) over the Macquarie-Castlereagh region for the 1895-2006 time horizon and the 2030s. Estimates of a median reduction in mean annual runoff of between 5% and 7% were derived from the models, with particular impacts in winter months. However, there was significant uncertainty across the two models; simulated changes in runoff for the SIMHYD model ranged from -19% to +20%, and -27% to +24% for the Sacramento model.

Chiew et al. (2011) investigated the effect of a 0.9°C increase in temperature for water availability in south eastern Australia (see Figure 12), based upon the corresponding pattern of climate change from 15 GCMs. The simulations showed a consensus across GCMs that summer runoff could increase with climate change and that winter runoff could decrease. Annually, there was consensus for a decrease in runoff along the south of the region but high uncertainty for the centre and north-west of the region. The results presented by Chiew et al. (2011) are largely consistent with a global-scale analysis presented by Gosling et al. (2010), which showed high agreement across 21 GCMs that annual runoff could decrease along the south-eastern coast of Australia under a 0.5°C warming scenario.

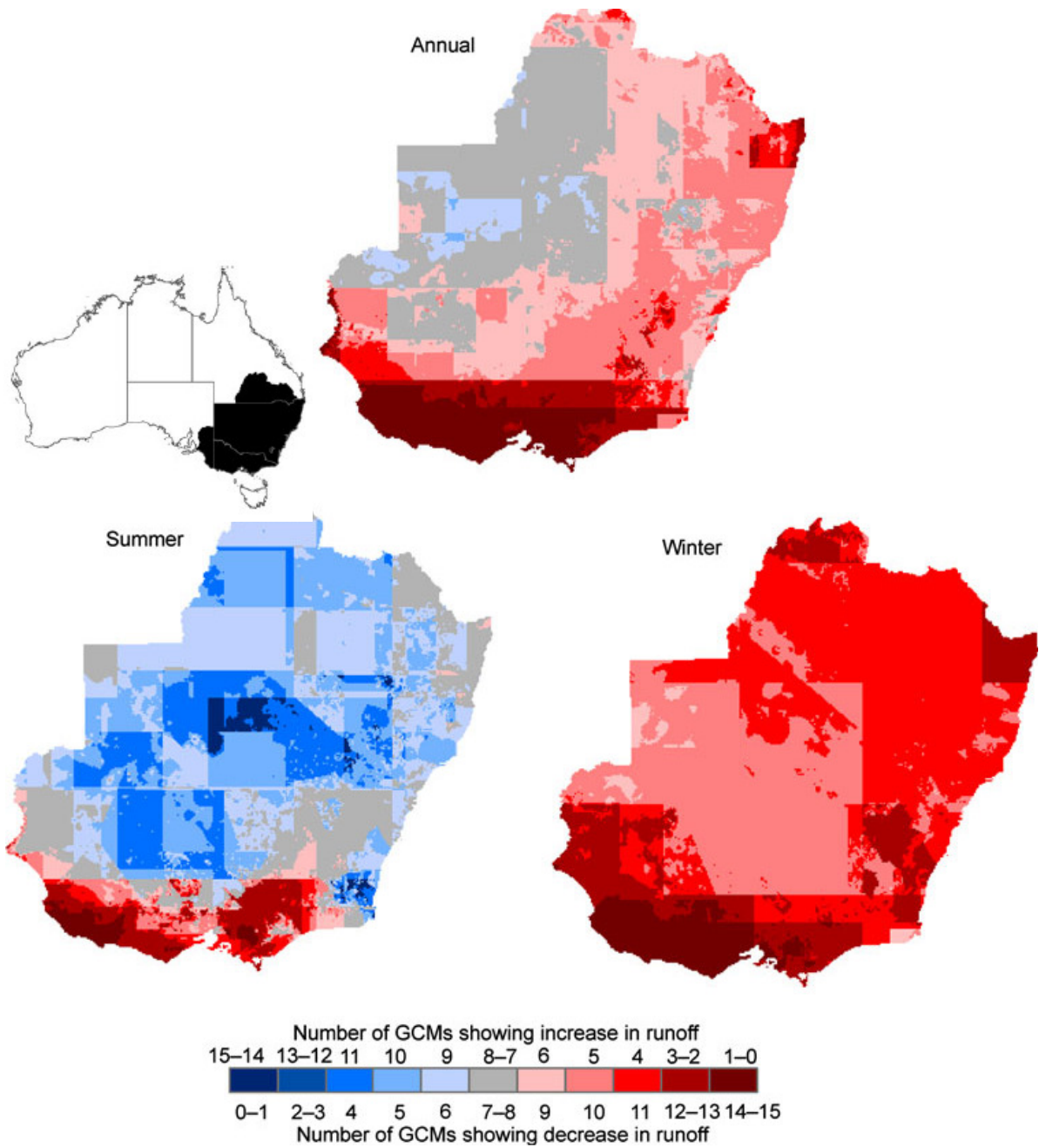


Figure 12. Number of GCMs (out of 15) showing a decrease (or increase) in future mean annual, summer (December–January–February), and winter (June–July–August) runoff, for south-eastern Australia under a 0.9°C increase in temperature. The figure is from Chiew et al. (2011).

AVOID Programme Results

To further quantify the impact of climate change on water stress and the inherent uncertainties, the AVOID programme calculated water stress indices for all countries reviewed in this literature assessment based upon the patterns of climate change from 21 GCMs (Warren et al., 2010), following the method described by Gosling et al. (2010) and Arnell (2004). This ensures a consistent methodological approach across all countries and takes consideration of climate modelling uncertainties.

Methodology

The indicator of the effect of climate change on exposure to water resources stress has two components. The first is the number of people within a region with an *increase in exposure to stress*, calculated as the sum of 1) people living in water-stressed watersheds with a significant reduction in runoff due to climate change and 2) people living in watersheds which become water-stressed due to a reduction in runoff. The second is the number of people within a region with a *decrease in exposure to stress*, calculated as the sum of 1) people living in water-stressed watersheds with a significant increase in runoff due to climate change and 2) people living in watersheds which cease to be water-stressed due to an increase in runoff. It is not appropriate to calculate the net effect of “increase in exposure” and “decrease in exposure”, because the consequences of the two are not equivalent. A water-stressed watershed has an average annual runoff less than 1000m³/capita/year, a widely used indicator of water scarcity. This indicator may underestimate water stress in watersheds where per capita withdrawals are high, such as in watersheds with large withdrawals for irrigation.

Average annual runoff (30-year mean) is simulated at a spatial resolution of 0.5°x0.5° using a global hydrological model, MacPDM (Gosling and Arnell, 2011), and summed to the watershed scale. Climate change has a “significant” effect on average annual runoff when the change from the baseline is greater than the estimated standard deviation of 30-year mean annual runoff: this varies between 5 and 10%, with higher values in drier areas.

The pattern of climate change from 21 GCMs was applied to MacPDM, under two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation scenario where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). Both scenarios assume that population changes through the 21st century following the SRES A1 scenario as implemented in IMAGE 2.3 (van Vuuren et al., 2007). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate

modelling, although it is acknowledged that only one impacts model is applied (MacPDM). Simulations were performed for the years 2030, 2050, 2080 and 2100. Following Warren et al. (2010), changes in the population affected by increasing or decreasing water stress represent the additional percentage of population affected due to climate change, not the absolute change in the percentage of the affected population relative to present day.

Results

The results for Australia are presented in Figure 13. Similar to the results presented by Rockstrom et al. (2009), Australia's population is not found to exhibit an increase or decrease in exposure to water stress with climate change.

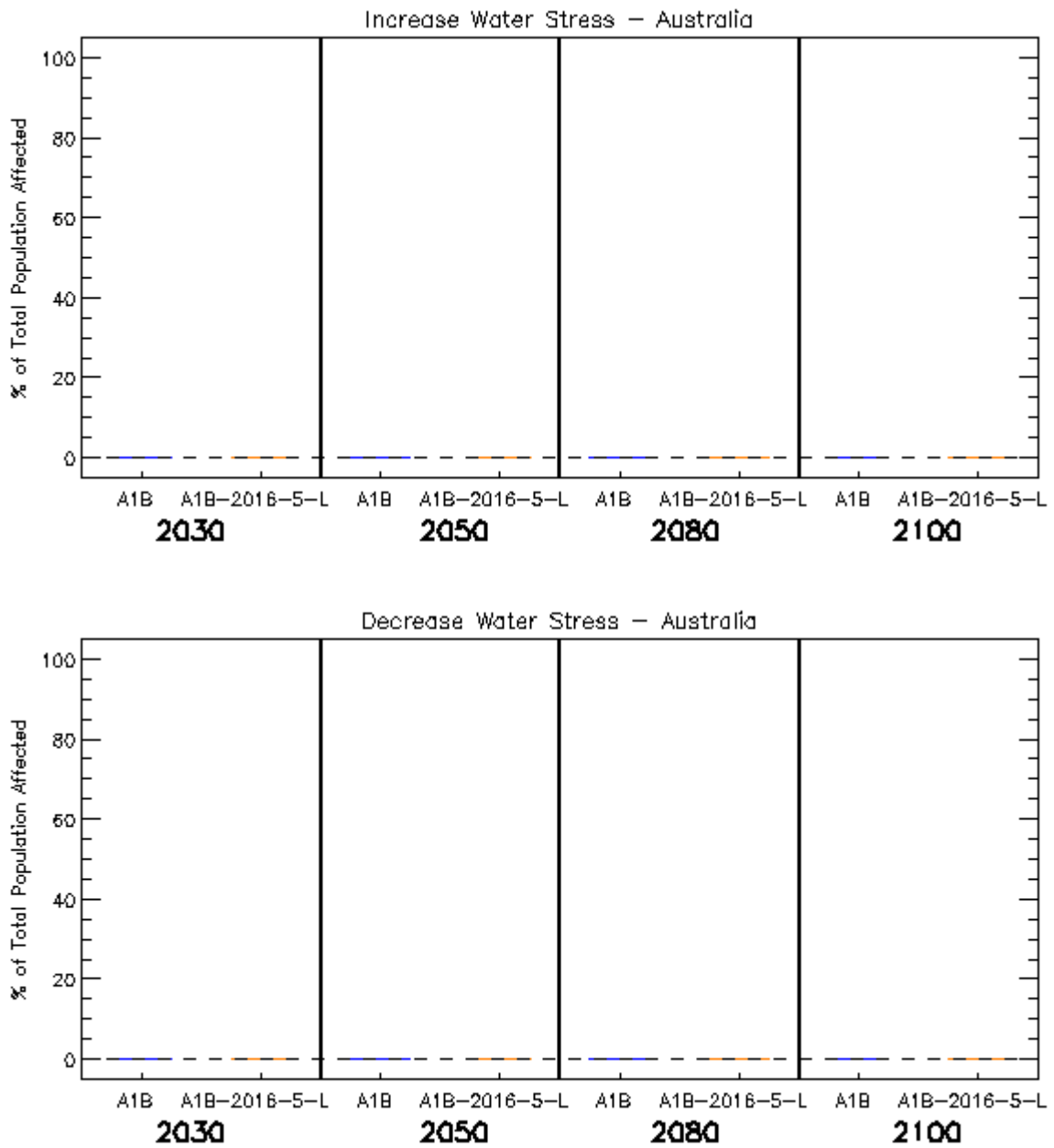


Figure 13. Box and whisker plots for the impact of climate change on increased water stress (top panel) and decreased water stress (bottom panel) in Australia, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).

Pluvial flooding and rainfall

Headline

The projections described in the IPCC AR4 noted a tendency for reduced rainfall over many regions of Australia but that extremes may increase. Work since then generally agrees with this, but has highlighted differences and uncertainties in changes at the regional level.

Supporting literature

Introduction

Pluvial flooding can be defined as flooding derived directly from heavy rainfall, which results in overland flow if it is either not able to soak into the ground or exceeds the capacity of artificial drainage systems. This is in contrast to fluvial flooding, which involves flow in rivers either exceeding the capacity of the river channel or breaking through the river banks, and so inundating the floodplain. Pluvial flooding can occur far from river channels, and is usually caused by high intensity, short-duration rainfall events, although it can be caused by lower intensity, longer-duration events, or sometimes by snowmelt. Changes in mean annual or seasonal rainfall are unlikely to be good indicators of change in pluvial flooding; changes in extreme rainfall are of much greater significance. However, even increases in daily rainfall extremes will not necessarily result in increases in pluvial flooding, as this is likely to be dependent on the sub-daily distribution of the rainfall as well as local factors such as soil type, antecedent soil moisture, land cover (especially urbanisation), capacity and maintenance of artificial drainage systems etc. It should be noted that both pluvial and fluvial flooding can potentially result from the same rainfall event.

Assessments that include a global or regional perspective

Climate change studies

The IPCC AR4 (2007a) provided only a brief assessment of changing precipitation in Australia, as no systematic evaluation existed at the time of preparation. The findings were that precipitation is likely to decrease in southern Australia in winter and spring, and very likely to decrease in south-western Australia during winter. Changes in rainfall in northern and central Australia are uncertain. Extremes of daily precipitation are very likely to increase. The most robust feature of projected change was a reduction in rainfall along the south coast in June-August (not including Tasmania), and a reduction in the annual mean. A decrease

was also evident in September-November. The percentage change for June-August in 2100 under A1B emissions for southern Australia has an inter-quartile range of -26% to -7%. Other aspects of simulated rainfall are less robust.

Washington et al. (2009) investigated climate change projections from an aggressive mitigation scenario (CO₂ stabilisation in 2100 at around 450ppm) compared with a non-mitigation scenario (CO₂ concentrations in 2100 of around 740ppm). For the 2080-2099 time horizon, they found that mitigation was associated with rainfall reductions of up to 20% compared to the non-mitigation scenario over northwest Australia, but generally lower changes elsewhere.

National-scale or sub-national scale assessments

Recent past

Choi et al. (2009) found that observed trends in total precipitation for Australia for the period 1955-2007 show an increase in annual precipitation of 1.5mm/decade, with -3.7mm/decade in winter, and 1.9mm/decade in summer. These trends are not statistically significant at the 95% level. Most extreme precipitation indices show significant trends at only a small proportion (30% or less) of weather stations, and there are no clear spatial clusters of change over the entire Asian region studied. Focusing on the Australian stations in the study, mostly insignificant positive trends of very wet day precipitation were found over western Australia, but negative trends were found in eastern Australia, particularly on the east coast where some trends were found to be significant.

Climate change studies

Monsoon rainfall projections and simulations vary substantially between climate models, so there is little confidence in model precipitation projections for northern Australia. A range of GCM and RCM studies have indicated a tendency for daily rainfall extremes to increase in the Australian region under enhanced greenhouse conditions. Typically, return periods of extreme rainfall events halve in late 21st century simulations, even in cases where the mean precipitation is decreasing. For example, Abbs (2004) explored dynamically downscaled (to 7km resolution) extreme rainfall events for northern New South Wales and southern Queensland. The author found that simulated extreme rainfall events compared well with observations, and enhanced greenhouse gas simulations for 2040 showed increases of around 30% in magnitude, with the current 1-in-40 year event becoming the 1-in-15 year event.

Suppiah et al. (2007) found that projections of rainfall changes under climate change for Australia showed both increases and decreases, though the dominant change was for rainfall decreases especially in the south during winter and spring. Compared with previous CSIRO projections, the updated projections were consistent but also showed a more widespread tendency for rainfall increases in summer in eastern Australia.

Perkins and Pitman (2009) noted that regional climate models often use an ensemble of all the available model data (e.g. the IPCC AR4 GCM dataset), but some regional assessments omit models based on specific criteria. In this study, models were selected based upon their ability to simulate observed distributions of daily temperature and precipitation data. This resulted in different regional projections for temperature, though there was little difference in precipitation results (see Figure 14). However, the models assessed as being better did simulate a larger increase in the maximum annual 1-day rainfall event, and a larger decrease in the number of rain days. Under SRES B1 emissions, Northern Australia was found to experience a small increase in mean precipitation by 2050 (0.3-1.0mm/d). Rainfall projections averaged over the best models showed an increase in precipitation over many Australian regions. The authors' results agree with conclusions from the IPCC AR4 (2007a) that a decline in precipitation is very likely along the southern coast, and intensifies with increased emissions and into the future. However, they disagree with the IPCC AR4 statement that changes in rainfall in Northern and Central Australia are uncertain, suggesting that these regions could experience increases, particularly as simulated in the better models. Moreover, Perkins and Pitman (2009) agree with the IPCC AR4 statement that extremes of daily precipitation will very likely increase, but note that the scale of increase is small and remains uncertain. They warn against the use of model ensemble averages, and recommend that researchers select individual models according to their specific requirements.

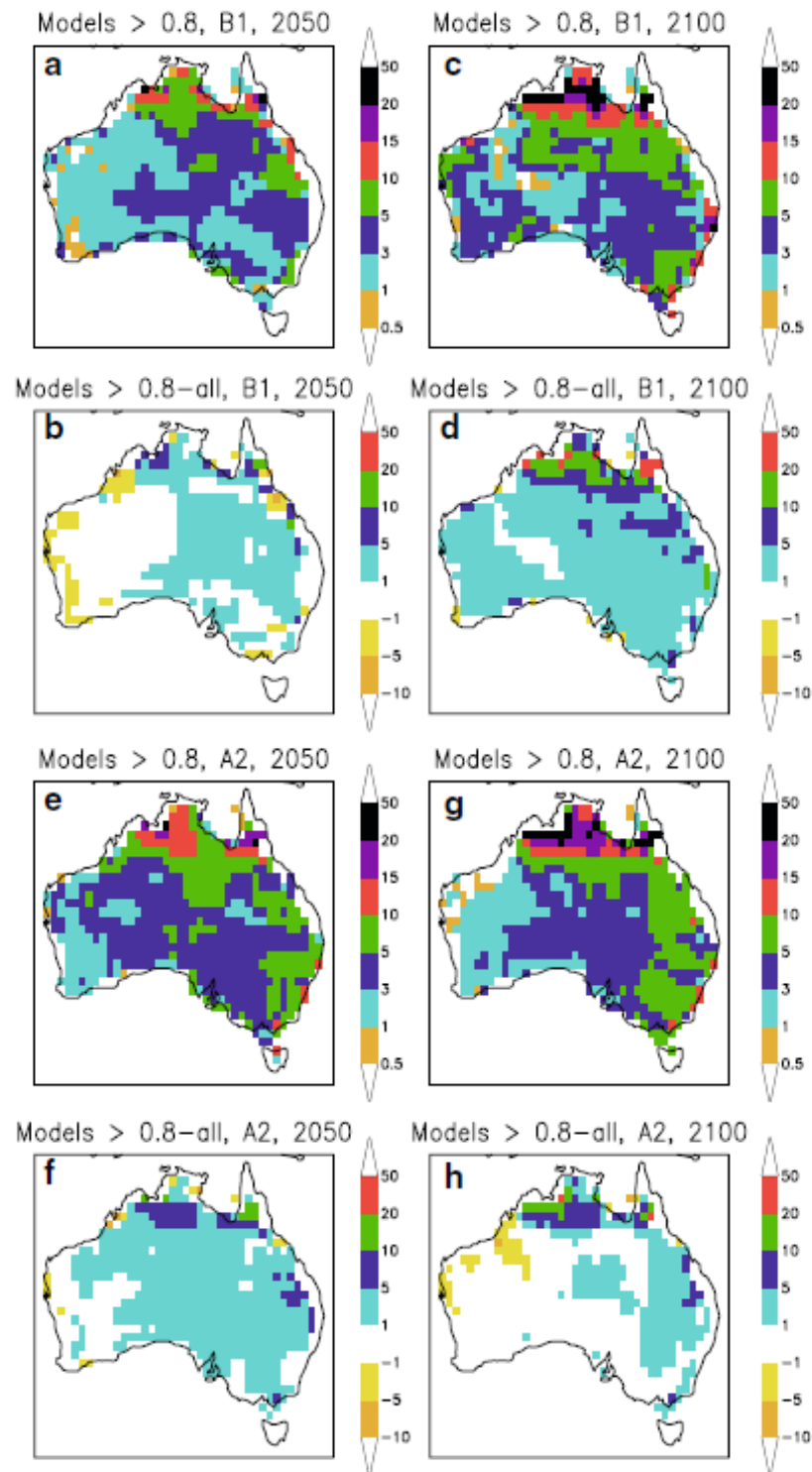


Figure 14. Change in P99 (the 99.7th percentile for precipitation; mm/day) over Australia simulated under the B1 emission scenarios for (a) IPCC AR4 climate models with skill scores over 0.8 in 2050, (b) difference of the >0.8 models minus the all-model ensemble in 2050; (c) AR4 models with skill scores over 0.8 in 2100, (d) difference of the >0.8 models minus the all-model ensemble in 2100, (e) as (a) but for the A2 emission scenario, (f) as (b) but for the A2 emission scenario, (g) as (c) but for the A2 emission scenario and (h) as (d) but for the A2 emission scenario. The figure is from Perkins and Pitman (2009).

Fluvial flooding

Headline

Floods in Queensland and New South Wales in December 2010 were the most significant in Australia since at least the 1970s in terms of extent and impact. Projections of fluvial flooding for Australia under climate change are, however, highly uncertain, largely due to climate modelling uncertainty. Some models project an increase in river discharge and some project a decrease. Recent simulations by the AVOID programme confirm this, with a majority of the simulations showing a decreasing trend in flood risk by the 2030s, but larger uncertainty later in the century. Improved hydro-climate projections at sub-national scale, with reliable probabilistic quantification of uncertainties, could help make more informed risk-based water sharing and management decisions. This is an important knowledge gap, which should be addressed.

Supporting literature

Introduction

This section summarises findings from a number of post IPCC AR4 assessments on river flooding in Australia to inform and contextualise the analysis performed by the AVOID programme for this project. The results from the AVOID work are discussed in the next section.

Fluvial flooding involves flow in rivers either exceeding the capacity of the river channel or breaking through the river banks, and so inundating the floodplain. A complex set of processes is involved in the translation of precipitation into runoff and subsequently river flow (routing of runoff along river channels). Some of the factors involved are; the partitioning of precipitation into rainfall and snowfall, soil type, antecedent soil moisture, infiltration, land cover, evaporation and plant transpiration, topography, groundwater storage. Determining whether a given river flow exceeds the channel capacity, and where any excess flow will go, is also not straightforward, and is complicated by the presence of artificial river embankments and other man-made structures for example. Hydrological models attempt to simplify and conceptualise these factors and processes, to allow the simulation of runoff and/or river flow under different conditions. However, the results from global-scale hydrological modelling need to be interpreted with caution, especially for smaller regions, due to the necessarily coarse resolution of such modelling and the assumptions and

simplifications this entails (e.g. a 0.5° grid corresponds to landscape features spatially averaged to around 50-55km for mid- to low-latitudes). Such results provide a consistent, high-level picture, but will not show any finer resolution detail or variability. Smaller-scale or catchment-scale hydrological modelling can allow for more local factors affecting the hydrology, but will also involve further sources of uncertainty, such as in the downscaling of global climate model data to the necessary scale for the hydrological models. Furthermore, the application of different hydrological models and analysis techniques often makes it difficult to compare results for different catchments.

Recently, Australia has been hit by several major flood disasters. Widespread severe flooding occurred in Queensland, New South Wales and Victoria during late 2010 and early 2011. The floods in Queensland and New South Wales in December 2010 were the most significant in Australia since at least the 1970s in terms of extent and impact (Braganza et al., 2011). There was further severe flooding in January 2011 in south-eastern Queensland, along with record-breaking floods in western and north-western Victoria. The cost of rebuilding infrastructure has been estimated at \$5 billion. According to the Garnaut Climate Change Review, there were 35 flood-related deaths and significant impacts on agriculture, mining and tourism (Hennessy and Overton, 2011).

Assessments that include a global or regional perspective

Climate change studies

Climate change scenarios generally show a tendency for rainfall extremes in Australia to become more intense, except in those regions and seasons where the mean precipitation declines substantially (CSIRO, 2007). However, the uncertainty in the projections of future precipitation and hence river discharge is large, with climate models often disagreeing on even the direction of change in rainfall (Chiew et al., 2011).

A global modelling study presented by Hirabayashi et al. (2008), based on simulations from a single GCM under the A1B emissions scenario, projected localised decreases in the return period of what was a 100-year flood event in the 20th century over the next few decades (2001-2030), primarily in small areas in Western, Northern and Eastern Australia. By the end of the century (2071-2100) a more widespread decrease in the return period of a 100-year flood down to 30 years or less was projected primarily over south-western Australia, the northern coast and in the East. Decreases were also found locally in the interior although no information was given about the significance or magnitude of flood events in these areas. Local increases in the return period of a 100-year flood, suggesting a reduction in flood frequency, were found in parts of Western Australia and the interior (Hirabayashi et al.,

2008). For the Murray-Darling River, the largest in Australia, Hirabayashi et al. (2008) projected a decrease in the return period of a 100-year flood event to 19 years even though the basin was projected to become drier on average, with peak flows occurring about half a month later on average. It should be noted, however, that results from studies that have applied only a single climate model or climate change scenario should be interpreted with caution. This is because they do not consider other possible climate change scenarios which could result in a different impact outcome, in terms of magnitude and in some cases sign of change.

In a study based on output from 19 GCMs under the A1B emissions scenario for the end of the 21st century (2081-2100), Nohara et al. (2006) found a large spread in the response of river flows in the Murray-Darling basin, with some models projecting an increase in river discharge and some projecting a decrease. This uncertainty was exacerbated by a poor model performance under current conditions as the effects of irrigation and dams were not taken into account by the river flow model that was applied (Nohara et al., 2006).

National-scale or sub-national scale assessments

Recent past

Identifying trends in flooding frequency over the past few decades is, however, difficult, due to the confounding influence of land-use changes and the construction of flood protection works and reservoirs (Westra, 2011). A preliminary study on trends in Australian flood data using 491 stations with minor anthropogenic influences and with annual maximum flood records of length between 30 and 97 years found approximately 30% of stations with a statistically significant trend at the 10% significance level, which were in a downward direction in southern parts of the Australian continent and an upward direction in the northern regions (Ishak et al., 2010).

Climate change studies

National-scale studies have found similar results to the global study of Nohara et al. (2006), with a large spread in the projected response of river discharge mostly due to uncertainty in the climate projections from GCMs (Chiew et al., 2008, Sun et al., 2011). In a study based on 15 climate models and assuming a medium warming scenario, Chiew et al. (2008) showed that projected changes in the 99th percentile (i.e. the flow level that is exceeded less than 1% of the time) across 183 sub-catchments of the Murray-Darling basin ranged from –40% to little change in the second-driest GCM projection, and from –20% to +40% in the second-wettest GCM projection. Such large uncertainty has also been found in other parts of

the continent, for example in southeast Australia (Chiew et al., 2011). However, it is difficult to separate a global warming signal from the large natural climate variability that has been observed over the last two centuries and that is also apparent in paleo-climate records (Chiew et al., 2011).

In the future, improved hydro-climate projections, with reliable probabilistic quantification of uncertainties, could help make more informed risk-based management decisions (Chiew et al., 2011). Furthermore, to date there has been little research on how changes in catchment antecedent moisture conditions could change due to global warming and how this could influence flood risk (Westra, 2011). It has been suggested that even under current climate variability the standard flood protection level of a 100-year flood event may need to be revised (Feddes, 2011).

AVOID programme results

To quantify the impact of climate change on fluvial flooding and the inherent uncertainties, the AVOID programme calculated an indicator of flood risk for all countries reviewed in this literature assessment based upon the patterns of climate change from 21 GCMs (Warren et al., 2010). This ensures a consistent methodological approach across all countries and takes consideration of climate modelling uncertainties.

Methodology

The effect of climate change on fluvial flooding is shown here using an indicator representing the percentage change in average annual flood risk within a country, calculated by assuming a standardised relationship between flood magnitude and loss. The indicator is based on the estimated present-day (1961-1990) and future flood frequency curve, derived from the time series of runoff simulated at a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$ using a global hydrological model, MacPDM (Gosling and Arnell, 2011). The flood frequency curve was combined with a generic flood magnitude–damage curve to estimate the average annual flood damage in each grid cell. This was then multiplied by grid cell population and summed across a region, producing in effect a population-weighted average annual damage. Flood damage is thus assumed to be proportional to population in each grid cell, not the value of exposed assets, and the proportion of people exposed to flood is assumed to be constant across each grid cell (Warren et al., 2010).

The national values are calculated across major floodplains, based on the UN PREVIEW Global Risk Data Platform (preview.grid.unep.ch). This database contains gridded estimates,

at a spatial resolution of 30 arc-seconds ($0.00833^\circ \times 0.00833^\circ$), of the estimated frequency of flooding. From this database the proportion of each $0.5^\circ \times 0.5^\circ$ grid cell defined as floodplain was determined, along with the numbers of people living in each $0.5^\circ \times 0.5^\circ$ grid cell in flood-prone areas. The floodplain data set does not include “small” floodplains, so underestimates actual exposure to flooding. The pattern of climate change from 21 GCMs was applied to MacPDM, under two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation policy where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). Both scenarios assume that population changes through the 21st century following the SRES A1 scenario as implemented in IMAGE 2.3 (van Vuuren et al., 2007). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate modelling, although it is acknowledged that only one impacts model is applied (MacPDM). Simulations were performed for the years 2030, 2050, 2080 and 2100. The result represents the change in flood risk due to climate change, not the change in flood risk relative to present day (Warren et al., 2010).

Results

The results for Australia are presented in Figure 15. By the 2030s, the models project a range of changes in mean fluvial flooding risk over Australia in both scenarios, with some models projecting decreases and others increases. However, the balance is more towards decreasing flood risk, with nearly 75% of models projecting a decrease. The largest decrease projected for the 2030s is a 60% reduction in the average annual flood risk, and the largest increase is 30%. The mean projection is approximately a 15% lower flood risk.

By 2100 the model projections become more balanced between increased and decreased flood risk in both scenarios, and the difference in projections from the different models also becomes greater. Both these aspects of the results are more pronounced for the A1B scenario than the mitigation scenario. Under the mitigation scenario, a majority of models still project a decreased flood risk (down to 70%), but several models project increased flood risk. The mean projection is a 10% decrease, and the upper projection is nearly a 50% increase. Under the A1B scenario, half the models project a decreased flood risk (down to 80%). The upper projection is a greater than 150% increase in annual average flood risk, with the mean projection being no change.

So for Australia, the models show a tendency towards decreasing flood risk at first, but later in the century the models are evenly divided between increases and decreases. The differences between the model projections are greater later in the century and particularly for A1B, suggesting larger model uncertainty.

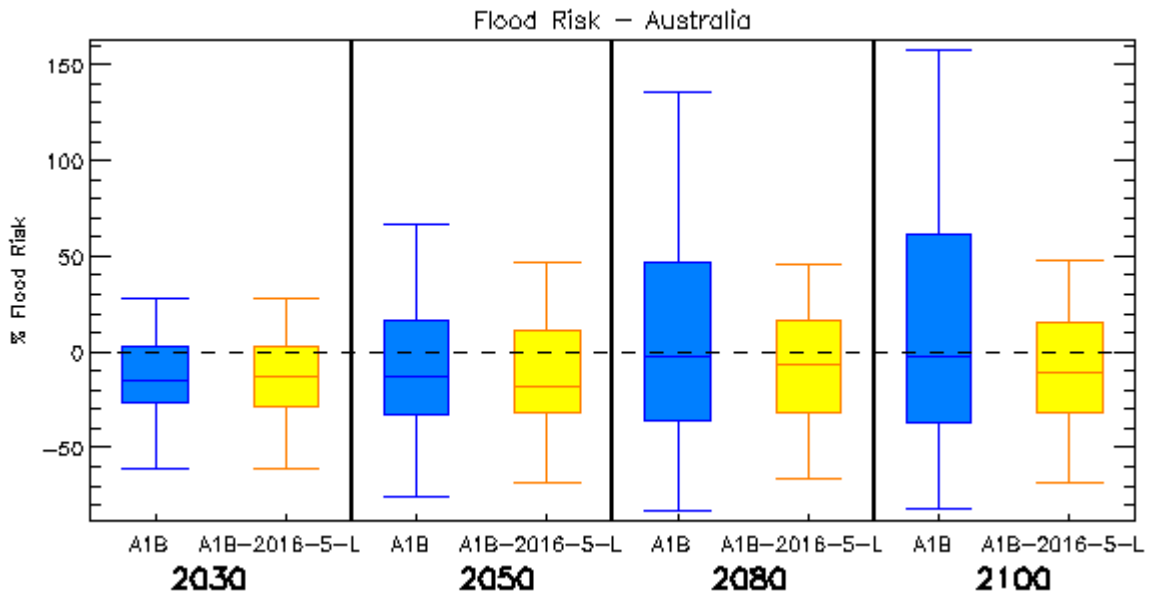


Figure 15. Box and whisker plots for the percentage change in average annual flood risk within Australia, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).

Tropical cyclones

Headline

A review of the current literature suggests that the *frequency* of tropical cyclones in the Southwest Pacific and South Indian Ocean basins could decrease in a warmer world, reducing the overall probability of tropical cyclone landfall on Australia's east and west coasts, respectively. A southward shift in tropical cyclone tracks has been reported by several studies, which may increase the risk of damage from land-falling cyclones near Australia's more heavily populated cities. Recent studies suggest that tropical cyclone *intensities* may increase with climate change, which could place vulnerable communities in the Torres Strait Islands at risk. However, there is a great deal of uncertainty surrounding how climate change may affect tropical cyclones, and extreme caution should be applied in interpreting results.

Supporting Literature

Introduction

Tropical cyclones are different in nature from those that exist in mid-latitudes in the way that they form and develop. There remains an overall large uncertainty in the current understanding of how tropical cyclones might be affected by climate change because conclusions are based upon a limited number of studies. Moreover, the majority of tropical-cyclone projections are from either coarse-resolution global models or from statistical or dynamical downscaling techniques. The former are unable to represent the most-intense storms, whereas the very patterns used for the downscaling may change in itself under climate change. To this end, caution should be applied in interpreting model-based results, even where the models are in agreement.

Assessments that include a global or regional perspective

Assessments of cyclone frequency

Several global-scale studies suggest a decrease in cyclone *frequencies* in the Southwest Pacific and South Indian Ocean (Gualdi et al., 2008, Oouchi et al., 2006, Sugi et al., 2009, Sugi et al., 2002, Zhao et al., 2009). Sugi et al. (2002) conducted a ten-year time-slice experiment (experiments over a short period of time to enable ensemble simulations using reasonable amounts of computational power) with the Japanese Meteorological Agency

(JMA) model at 120km resolution under a 2xCO₂ emissions scenario. The model simulated a 31% decrease in Southwest Pacific tropical cyclone frequencies and a 57% decrease in the South Indian Ocean. Gualdi et al. (2008) found a 22% decrease in the Southwest Pacific and a 14% decrease in the South Indian Ocean, using the 120km Italian GCM SINTEX-G model, under a 2x CO₂ emissions scenario. In a much higher-resolution study, Zhao et al. (2009) applied the 50km resolution GFDL GCM with four future sea surface temperature (SST) distributions simulated by other GCMS, from 1) the CMIP3 multi-model dataset ensemble mean, 2) the HadCM3 GCM, 3) the GFDL GCM, and 4) the ECHAM5 GCM. The SSTs distributions were for the A1B emissions scenario for the time horizon 2081-2100. In all four experiments, the frequencies of cyclones in the Southwest Pacific and South Indian Ocean decreased: in the former basin, the magnitudes of the decrease ranged from 31% to 48%, while in the latter the range was 13-41%. Oouchi et al. (2006) employed the 20km JMA model in a 10 year timeslice under the A1B emissions scenario and noted a 28% decrease in the South Indian Ocean and a 43% decrease in the Southwest Pacific. Sugi et al. (2009) conducted a timeslice experiment with the JMA model, operating at 60km and 20km resolutions respectively, with simulated SSTs from three individual GCMs and the CMIP3 multi-model dataset ensemble-mean (similar to Zhao et al. (2009)). This meant Sugi et al. (2009) conducted eight projections, all of which were under the A1B emissions scenario. For both basins near Australia, seven of the eight experiments projected a decrease in cyclone frequencies, with the eighth experiment simulating a slight increase. Most of the decreases ranged from 20-40%, with two experiments showing decreases of greater than 60% in the Southwest Pacific.

There is therefore considerable evidence for an overall decrease in the frequency of landfalling cyclones near Australia, in the range of 20-40%, although the southward shift in cyclone tracks may lead to an increase in landfalling storms—and hence in damages—in heavily populated regions of the east coast. Most authors have attributed this decrease to the projection of below-global-mean increases in SSTs in the Southern Hemisphere, while increases in vertical wind shear and decreases in relative humidity—which suppress cyclone formation—are likely to be much closer to the global means for those quantities. For example, Yu et al. (2010) found that the Southwest Pacific showed the smallest projected SST warming by 2100 of any tropical-cyclone basin, using 18 climate models from the CMIP3 multi-model dataset under the A1B emissions scenario.

Assessment of cyclone intensity

The *intensity* of cyclones near Australia is projected to increase, particularly for the most extreme cyclones. Leslie et al. (2007) found that the frequency of strong tropical cyclones

(defined as those with wind speeds greater than 30 m s^{-1}) across a six-member ensemble of a single GCM, doubled by 2050 relative to 1970-2000, under the IPCC IS92a emissions scenario (see Figure 16). This led the authors to conclude that Australia could experience storms more intense than any in the observed record. Walsh et al. (2004) conducted a $3\times\text{CO}_2$ experiment with the CSIRO RCM at 30km resolution in the Southwest Pacific. Over the 30 year simulation, the model simulated a 56% increase in the number of cyclones with a wind speeds greater than 30 m s^{-1} . Similar to Leslie et al. (2007), Walsh et al. (2004) found an increase in the number of storms tracking south of 30°S . When combined with the increased frequency of strong cyclones, this shift in tracks suggests that the southern half of Australia's east coast could experience an increase in the frequency *and* magnitude of extreme cyclones in a warmer world.

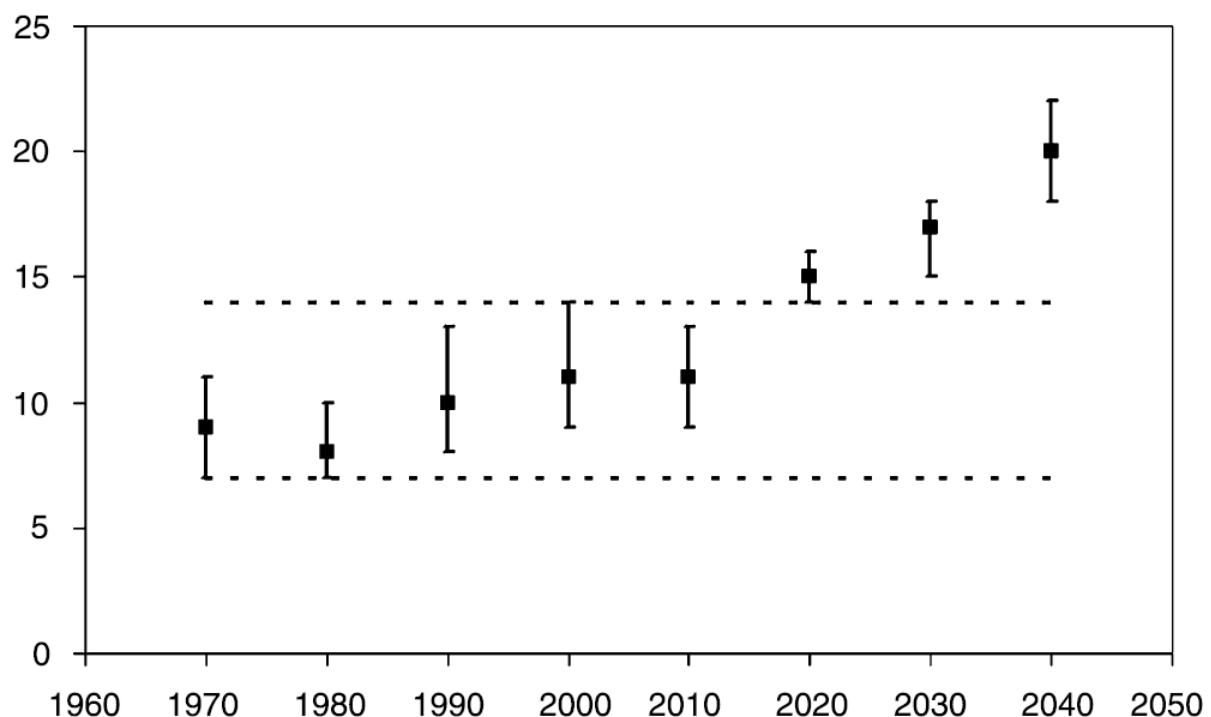


Figure 16. Time series of ensemble-mean (six GCMs) number of strong tropical cyclones (vertical axis) in each decade shown by the filled box) under the IPCC IS92a emissions scenario. The highest and lowest numbers of tropical cyclones over the six-member ensemble are shown by the vertical line centered on the box. The horizontal dashed line shows the range of ensemble mean decadal number of tropical cyclones from the control run (CO_2 emissions stabilised at 2000-level), giving an estimate of the possible range due to natural variability. The figure is from Leslie et al. (2007).

Assessment of cyclone damages

The projected increase in tropical-cyclone intensities near Australia puts vulnerable communities at risk from stronger winds, greater storm surges and heavier rainfall. The communities of the Torres Strait Islands are particularly vulnerable to cyclone damage (Green et al., 2009). These low-lying islands have considerable exposure to risks

associated with cyclone damage, but few available resources for adaptation. Green et al. (2009) concluded that if the intensity of tropical cyclones increases in a warmer world—which the studies described previously suggest is likely—then the Torres Strait Islands could be at increased risk of inundation from storm surges and flooding from extreme rainfall. The storm surge risk is exacerbated by projected SLR. Green et al. (2009) describe a probable increase in the number of injuries and accidental deaths, particularly in more-remote communities where rescue operations are difficult.

Even in combination with the decreases in cyclone frequency, the projected strengthening of Southwest Pacific and South Indian Ocean cyclones, particularly the most intense cyclones, is projected to slightly increase cyclone damages in Australia. Mendelsohn et al. (2011) applied the cyclone “seeding” method of Emanuel et al. (2008) to the climate simulations from four GCMs under the A1B emissions scenario. They then constructed a damage model to estimate the damages from each landfalling storm. The technique applied in the study “seeds” large numbers of tropical-cyclone vortices into each basin, then uses the models’ large-scale climate fields (e.g., SSTs, wind shear, relative humidity) to determine whether the storms grow into cyclones or simply decay. The technique has shown considerable skill at simulating both frequency and intensity of storms over the past several decades. Mendelsohn et al. then constructed a damage model to estimate the damages from each landfalling storm. In the Emanuel et al. (2008) method, cyclone-like disturbances are randomly generated in the large-scale environment estimated by a climate model under a climate change scenario. The storms can then grow or decay, as determined by the climate model’s atmospheric conditions and the underlying SST. The Mendelsohn et al. (2011) method separates the additional damages from the impact of climate change on tropical cyclones from the additional damages due to future economic development. This is accomplished through applying the damages from both present-day and future tropical cyclones to the projected economic conditions in 2100 (the “future baseline”). Against a future baseline of \$233.9 million, two of the four GCMs considered by Mendelsohn et al. (2011) simulated an increase in cyclone damages in Australia: the CNRM model (\$39.6 million increase) and the ECHAM5 model (\$41.6 million). The other two models—GFDL and MIROC—showed virtually no change in damages.

National-scale or sub-national scale assessments

Assessments of cyclone frequency

Several global-scale studies, described previously, suggest a decrease in cyclone *frequencies* in the Southwest Pacific and South Indian Ocean (Gualdi et al., 2008, Oouchi et

al., 2006, Sugi et al., 2009, Sugi et al., 2002, Zhao et al., 2009), and this is confirmed in the consensus across a number of smaller-scale assessments that the frequency of tropical cyclones in the Southwest Pacific and Southwest Indian Oceans could decrease under climate change (Lavender and Walsh, 2011, Nguyen and Walsh, 2001, Walsh and Katzfey, 2000).

Lavender and Walsh (2011) applied the CSIRO Conformal-Cubic Atmospheric Model (CCAM) at 60 km resolution, under SRES A2 emissions. In separate experiments, the CCAM simulation showed large similarity with the large-scale atmospheric conditions simulated by other lower resolution climate models, including the GFDL GCM (CM2.1), the Max Planck Institute GCM (ECHAM5) and the CSIRO GCM (Mk 3.5) (all under SRES A2 emissions too); see Figure 17. The SSTs from each of these models were used as lower-boundary conditions in their respective experiments. Two 20-year periods were analyzed: 2046-2065 and 2081-2100. When a tropical cyclone was detected in the CCAM simulations, a further downscaling to 15km was conducted to better resolve the cyclone's intensity. In all three experiments, the frequency of tropical cyclones near the Australian coastline decreased by the 2081-2100 period; the range of simulated decreases was 27-38%. The experiments differed in the spatial pattern of decreases: the GFDL model projected a greater decrease along the east coast, whilst the ECHAM GCM favoured decreases along the west coast. All models also showed a southward shift in the remaining cyclone tracks, with increases in the number of cyclones making landfall in the heavily populated areas of southern Queensland and northern New South Wales. Such increases have the potential to significantly enhance damages from landfalling cyclones. Lavender and Walsh (2011) attributed this poleward shift in cyclone tracks to anomalous descending motion over northern Australia and anomalous ascent to the south; these shifts were linked to large-scale tropical-circulation changes in the three driving GCMs. A similar southward shift in tropical-cyclone tracks was found by Leslie et al. (2007) using the Oklahoma University GCM (OU-CGCM) with a 50 km nested regional domain over the Southwest Pacific. Regional modelling studies presented by Walsh and Katzfey (2000) and Nguyen and Walsh (2001) also suggested that Southwest Pacific cyclone tracks could shift southward in a warmer world.

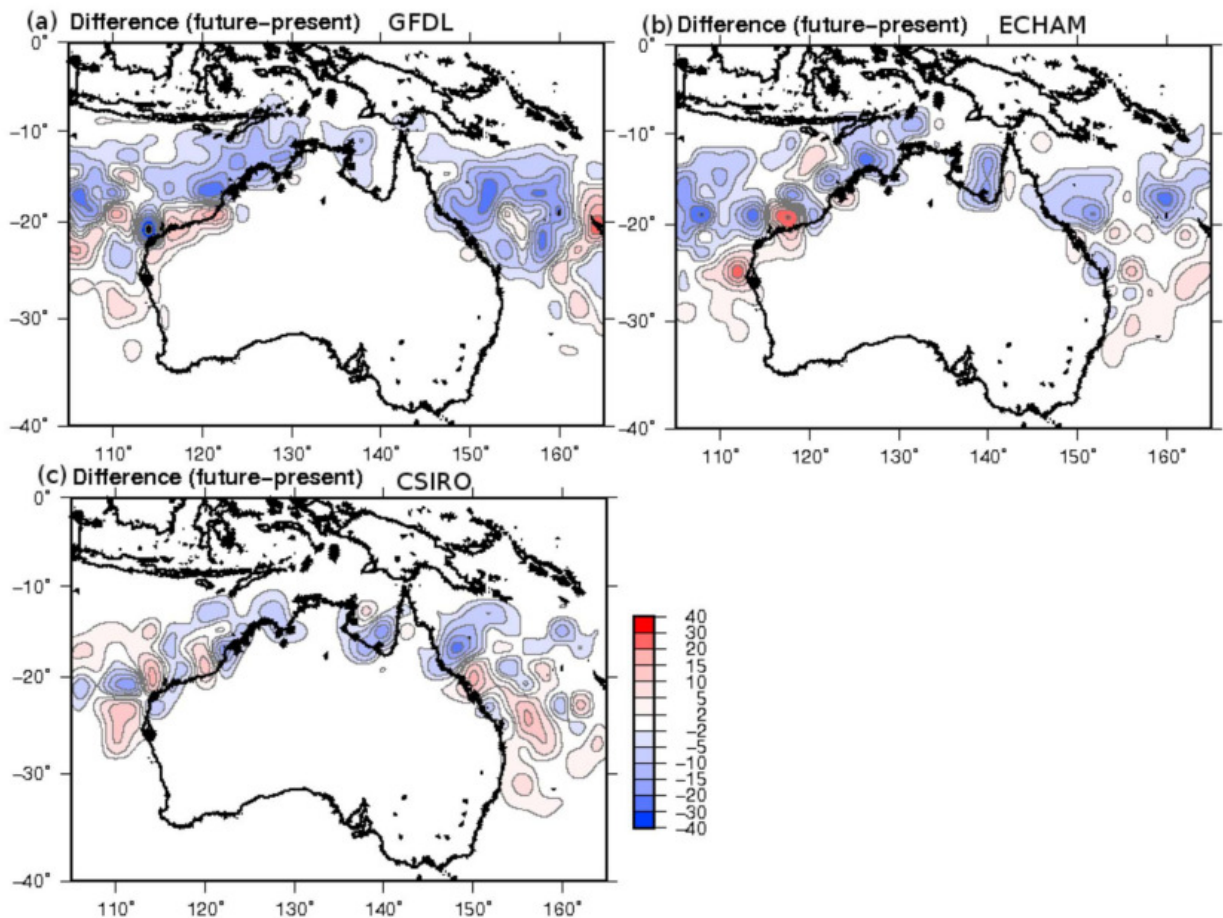


Figure 17. The difference in the frequencies of simulated cyclone tracks under present-day (1981-2000) and with climate change (2081-2100 under the SRES A2 scenario) simulations, using the 15km resolution CCAM RCM driven by the large-scale atmospheric conditions and SSTs from the (a) GFDL GCM, (b) the ECHAM5 GCM and (c) the CSIRO GCM. Whilst all three GCMs display a decrease in cyclone counts near Australia, the ECHAM5 and CSIRO GCMs also show a southward shift in cyclone tracks, suggesting more landfalling cyclones in eastern Australia. The figures is from Lavender et al. (Lavender and Walsh, 2011).

Assessment of cyclone damages

Stewart and Wang (2011) assessed the impact of changes in tropical cyclone frequency and wind speed on damages in four Australian locations. Assuming a 'business as usual' scenario (no adaptation measures), Stewart and Wang (2011) showed that a changing climate could increase mean wind damage losses for Cairns, Townsville, Rockhampton and Brisbane by a total of up to \$2.8, \$7.1 and \$15 billion by 2030, 2050 and 2100, respectively, assuming a 4% discount rate. Moreover, the authors found that there is a 90% chance that moderate (25% reduction in cyclone frequency, 10% increase in wind speeds) and significant (no change in cyclone frequency, 20% increase in wind speeds) wind change scenarios could increase total damages by more than \$1.6 billion and \$5.9 billion by 2100, respectively. Stewart and Wang (2011) concluded that there is clearly a high likelihood of

large potential economic losses if there is no change to building standards, and suggests that climate adaptation strategies are needed to ameliorate these losses.

Coastal regions

Headline

Australia is characterised by densely and increasingly populated coastal areas; 80% of the population live within 50 km of the coast. Several studies suggest that Sea Level Rise (SLR) could increase coastal flooding in Australia. However, the absolute magnitude of the simulated impacts tend to be relatively small when compared with other countries across the globe. This is due to several assumptions, including: a decline in population growth from 2050 onwards; an increase in GDP and coastal protection in the future; and an improved adaptive capacity for the region as a whole in the future.

Supporting Literature

Assessments that include a global or regional perspective

Climate change studies

The IPCC AR4 concluded that at the time, understanding was too limited to provide a best estimate or an upper bound for global SLR in the twenty-first century (IPCC, 2007b). However, a range of SLR, excluding accelerated ice loss effects was published, ranging from 0.19m to 0.59m by the 2090s (relative to 1980-2000), for a range of scenarios (SRES A1FI to B1). The IPCC AR4 also provided an illustrative estimate of an additional SLR term of up to 17cm from acceleration of ice sheet outlet glaciers and ice streams, but did not suggest this is the upper value that could occur. Although there are published projections of SLR in excess of IPCC AR4 values (Nicholls et al., 2011), many of these typically use semi-empirical methods that suffer from limited physical validity and further research is required to produce a more robust estimate. Linking sea level rise projections to temperature must also be done with caution because of the different response times of these two climate variables to a given radiative forcing change.

Nicholls and Lowe (2004) previously showed that mitigation alone would not avoid all of the impacts due to rising sea levels, adaptation would likely be needed too. Recent work by van Vuuren et al. (2011) estimated that, for a world where global mean near surface temperatures reach around 2°C by 2100, global mean SLR could be 0.49m above present levels by the end of the century. Their sea level rise estimate for a world with global mean temperatures reaching 4°C by 2100 was 0.71m, suggesting around 40% of the future increase in sea level to the end of the 21st century could be avoided by mitigation. A

qualitatively similar conclusion was reached in a study by Pardaens et al. (2011), which examined climate change projections from two GCMs. They found that around a third of global-mean SLR over the 21st century could potentially be avoided by a mitigation scenario under which global-mean surface air temperature is near-stabilised at around 2°C relative to pre-industrial times. Under their baseline business-as-usual scenario the projected increase in temperature over the 21st century is around 4°C, and the sea level rise range is 0.29-0.51m (by 2090-2099 relative to 1980-1999; 5% to 95% uncertainties arising from treatment of land-based ice melt and following the methodology used by the IPCC AR4). Under the mitigation scenario, global mean SLR in this study is projected to be 0.17-0.34m.

The IPCC 4th assessment (IPCCb) followed Nicholls and Lowe (2004) for estimates of the numbers of people affected by coastal flooding due to sea level rise. Nicholls and Lowe (2004) projected for the Pacific Large Island region that an additional 100 thousand people per year could be flooded due to sea level rise by the 2080s relative to the 1990s for the SRES A2 scenario (note this region also includes other countries, such as New Zealand). However, it is important to note that this calculation assumed that protection standards increased as GDP increased, although there is no additional adaptation for sea level rise. More recently, Nicholls et al. (2011) also examined the potential impacts of sea level rise in a scenario that gave around 4°C of warming by 2100. Readings from Figure 3 from Nicholls et al. (2011) for the Pacific Ocean large islands region suggest that less than an approximate 1 million additional people could be flooded for a 0.5 m SLR (assuming no additional protection). Nicholls et al. (2011) also looked at the consequence of a 2m SLR by 2100, however as we consider this rate of SLR to have a low probability we don't report these figures here.

Useful projections of the impact of climate change and SLR on the coastal regions of Australia, based upon a global-scale assessment, are presented in the IPCC AR4 (Nicholls et al., 2007). Nicholls et al. (2007) make several references to previous work described by Nicholls and Lowe (2004). By considering SLR scenarios under four SRES emissions scenarios (A1FI, A2, B1 and B2), Nicholls et al. (2007) estimated the average annual number of coastal flood victims due to SLR in the 2020s, 2050s and 2080s, for six regions across the globe (Australia, Europe, Asia, North America, Latin America, and Africa). The study assumed that the level of coastal protection improved as GDP per capita increased with time. However, Nicholls et al. (2007) assumed that storm intensity does not change with climate change. Increased storm intensity could exacerbate impacts, so some estimates may be underestimated. Without sea-level rise, coastal flooding was projected to diminish as a problem under the SRES scenarios while, with sea-level rise, the coastal flood problem

increases by the 2080s, particularly under the A2 scenario. The study found that Asia and Africa experience the largest impacts (4-7 million extra people flooded annually in Asia in the 2080s under SRES A2 due to SLR). However, the results presented by Nicholls et al. (2007) for Australia, suggest that SLR, under the emissions scenarios they considered, could have no additional effect beyond present day SLR, on coastal flooding.

Hanson et al. (2010) investigated port city population exposure to global SLR, natural and human subsidence/uplift, and more intense storms and higher storm surges, for 136 port cities across the globe. Future city populations were calculated using global population and economic projections, based on the SRES A1 scenario up to 2030. The study accounted for uncertainty on future urbanization rates, but estimates of population exposure were only presented for a rapid urbanisation scenario, which involved the direct extrapolation of population from 2030 to 2080. All scenarios assumed that new inhabitants of cities in the future will have the same relative exposure to flood risk as current inhabitants. The study is similar to a later study presented by Hanson et al. (2011) except here, different climate change scenarios were considered, and published estimates of exposure are available for more countries. Future water levels were generated from temperature and thermal expansion data related to greenhouse gas emissions with SRES A1B (un-mitigated climate change) and under a mitigation policy where emissions peak in 2016 and decrease subsequently at 5% per year to a low emissions floor (2016-5-L). Table 9 shows the aspects of SLR that were considered for various scenarios and Table 10 displays regional port city population exposure for each scenario in the 2030s, 2050s and 2070s. The results show that Australia is one of the countries where port cities are impacted least by SLR, in absolute terms (e.g. compare the projections in Table 10 with the estimates for exposure in the absence of climate change that are presented in Table 11). Hanson et al. (2010) also demonstrated that an aggressive mitigation scenario could avoid an exposure of around 6,000 people in Australia, relative to un-mitigated climate change (see Table 11).

Scenario		Water levels				
Code	Description	Climate			Subsidence	
		More intense storms	Sea-level change	Higher storm surges	Natural	Anthropogenic
FNC	Future city	V	x	x	X	x
FRSLC	Future City Sea-Level Change	V	V	x	V	x
FCC	Future City Climate Change	V	V	V	V	x
FAC	Future City All Changes	V	V	V	V	V

Table 9. Summary of the aspects of SLR considered by Hanson et al. (2010). 'V' denotes that the aspect was considered in the scenario and 'x' that it was not.

Rapid urbanisation projection																	
2030						2050						2070					
Country	Ports	Water level projection				Country	Ports	Water level projection				Country	Ports	Water level projection			
		FAC	FCC	FRSL C	FNC			FAC	FCC	FRSLC	FNC			FAC	FCC	FRSL C	FNC
CHINA	15	17,100	15,500	15,400	14,600	CHINA	15	23,000	19,700	18,700	17,400	CHINA	15	27,700	22,600	20,800	18,600
INDIA	6	11,600	10,800	10,300	9,970	INDIA	6	16,400	14,600	13,600	12,500	INDIA	6	20,600	17,900	15,600	13,900
US	17	8,990	8,960	8,830	8,460	US	17	11,300	11,200	10,800	9,970	US	17	12,800	12,700	12,100	10,700
JAPAN	6	5,260	4,610	4,430	4,390	JAPAN	6	6,440	5,280	5,000	4,760	JAPAN	6	7,800	5,970	5,580	5,070
INDONESIA	4	1,420	1,200	1,200	1,170	INDONESIA	4	2,110	1,610	1,610	1,500	INDONESIA	4	2,680	1,830	1,830	1,530
BRAZIL	10	833	833	833	802	BRAZIL	10	929	929	929	879	BRAZIL	10	940	940	940	864
UK	2	497	497	478	459	UK	2	609	609	564	521	UK	2	716	716	640	569
CANADA	2	459	433	422	405	CANADA	2	549	512	486	457	CANADA	2	614	585	545	489
SOUTH KOREA	3	344	344	331	441	SOUTH KOREA	3	361	361	341	318	SOUTH KOREA	3	377	377	325	303
GERMANY	1	257	257	253	248	GERMANY	1	287	287	273	269	GERMANY	1	309	309	290	280
RUSSIA	1	177	177	177	177	RUSSIA	1	202	202	173	173	RUSSIA	1	226	226	197	169
AUSTRALIA	5	162	162	157	157	AUSTRALIA	5	197	197	191	181	AUSTRALIA	5	196	196	186	175
SAUDI ARABIA	1	24	24	24	22	SAUDI ARABIA	1	33	33	33	27	SAUDI ARABIA	1	38	38	38	29
SOUTH AFRICA	2	30	30	30	29	SOUTH AFRICA	2	28	28	28	27	SOUTH AFRICA	2	30	30	30	27
FRANCE	1	15	15	15	15	FRANCE	1	19	19	19	17	FRANCE	1	23	23	23	18
ITALY	1	2	2	2	2	ITALY	1	4	4	4	3	ITALY	1	6	6	6	4
MEXICO	0	0	0	0	0	MEXICO	0	0	0	0	0	MEXICO	0	0	0	0	0

Table 10. National estimates of port city population exposure (1,000s) for each water level projection (ranked according to exposure with the FAC (Future City All Changes) scenario) under a rapid urbanisation projection for the 2030s, 2050s and 2070s. Estimates for present day exposure and in the absence of climate change (for 2070 only) for comparison are presented in Table 11. Data is from Hanson et al. (2010) and has been rounded down to three significant figures.

Country	Ports	Population exposure				Exposure avoided
		Current	2070. Rapid urbanisation, FAC water level scenario			
			No climate change	A1B un-mitigated	Mitigated (2016-5-L)	
CHINA	15	8,740	18,600	27,700	26,500	1,140
UNITED STATES	17	6,680	10,700	12,800	12,300	505
RUSSIA	1	189	169	226	197	28
JAPAN	6	3,680	5,070	7,800	7,290	515
SOUTH AFRICA	2	24	27	30	29	0
INDIA	6	5,540	13,900	20,600	18,900	1,670
BRAZIL	10	555	864	940	926	14
MEXICO	0	0	0	0	0	0
CANADA	2	308	489	614	599	15
AUSTRALIA	5	99	175	196	190	6
INDONESIA	4	602	1,530	2,680	2,520	156
SOUTH KOREA	3	294	303	377	343	34
UK	2	414	569	716	665	51
FRANCE	1	13	18	23	20	2
ITALY	1	2	4	6	6	0
GERMANY	1	261	280	309	295	15
SAUDI ARABIA	1	15	29	38	35	3

Table 11. Exposed port city population (1,000s) in present (current), and in the 2070s in the absence of climate change (no climate change), with unmitigated climate change (A1B un-mitigated), and mitigated climate change (mitigated 2016-5-L), under the rapid urbanisation and FAC (Future City All Changes) water level scenarios. The final column shows the potential avoided exposure, as a result of mitigation. Data is from Hanson et al. (2010) and has been rounded down to three significant figures.

To further quantify the impact of SLR and some of the inherent uncertainties, the DIVA model was used to calculate the number of people flooded per year for global mean sea level increases (Brown et al., 2011). The DIVA model (DINAS-COAST, 2006) is an integrated model of coastal systems that combines scenarios of water level changes with socio-economic information, such as increases in population. The study uses two climate scenarios; 1) the SRES A1B scenario and 2) a mitigation scenario, RCP2.6. In both cases an SRES A1B population scenario was used. The results are shown in Table 12.

	A1B		RCP	
	Low	High	Low	High
Additional people flooded (1000s)	6.73	62.81	4.30	27.82
Loss of wetlands area (% of country's total wetland)	16.62%	23.89%	12.63%	22.83%

Table 12. Number of additional people flooded (1000s), and percentage of total wetlands lost by the 2080s under the high and low SRES A1B and mitigation (RCP 2.6) scenarios (Brown et al., 2011).

National-scale or sub-national scale assessments

Climate change studies

Whilst the global assessment of SLR impacts on coastal flooding for Australia suggests SLR may not result in any major increase in additional people flooded than at present (Nicholls, 2004, Nicholls et al., 2007), a number of finer scale regional studies suggest a less optimistic outlook for parts of Australia when non-population based impacts are considered. McInnes et al. (2003) investigated the effects of a 10% increase in tropical cyclone intensity for Cairns, Australia. To this end, the method is somewhat advantageous to that applied by Nicholls et al. (2004, 2007) because the results implied more coastal flooding than SLR alone would suggest. The study found that the area of Cairns at risk of inundation by a 1-in-100 year storm surge is likely to more than double by 2050. Similarly, negative impacts are estimated for Australia based on small-scale local assessments. Hennecke et al. (2004) applied a GIS in combination with readily available data and two coastal behaviour models (the Bruun-GIS Model and the Aggradation Model) to simulate shoreline recession caused by SLR for Collaroy and Narrabeen Beach in Sydney, New South Wales, Australia. The potential impacts of a 50-year design storm were considered in conjunction with SLR. The study estimated that at Collaroy/Narrabeen beach, a SLR of 0.2m by 2050 combined with a 50-year storm event could result in coastal recession exceeding 110m. This could be associated with losses of around \$184 million. More recently, Akumu et al. (2010) projected

wetland area losses of around 55% by 2050 for inland open waters in north-eastern NSW, Australia.

In Australia, between 187,000 and 274,000 residential buildings (valued between AUD51 and AUD72 billion, based on 2008 figures) and between 5,800 and 8,600 commercial buildings (valued between AUD58 and AUD81 billion) are exposed to inundation and erosion at a SLR of 1.1m, assuming a high end scenario for 2100, with Queensland and New South Wales most impacted (Australian Government Department of Climate Change and Energy Efficiency, 2011).

In the Hunter, Central and Lower North Coast region of New South Wales, there are significant residential and industrial areas located in low-lying areas (below 2.5m) including 31,000 householders with 8.5% of the total population in the region. Moreover, 16% of the total population is directly exposed to 1-in-100 year flood events, with 25% of all householders in low-income, and the elderly 17% of the total exposed population. There are more intangible costs related to health effects, stress and disruption of services perceived by affected householders than tangible costs (Kinrade et al., 2010).

A national assessment of the impacts of climate change on human health includes some important estimates of the impacts of SLR on the number of people exposed to coastal flooding in Australia, and largely supports the more optimistic findings of the global assessments presented by Nicholls (2004, 2007) and Hanson et al. (2010); that SLR could have a relatively minimal impact on populations affected by flooding in Australia. McMichael et al. (2003) presents simulations for Australia that considered low, medium and high scenarios of SLR (19cm, 45cm and 80cm respectively), coastal population changes, subsidence (where appropriate), and flood defence standards derived from GDP per capita data, identical to the methods applied by Nicholls (1999). The study did not account for any change in the frequency or intensity of storm surges. Table 13 shows the number of people exposed to coastal flooding in 1990 and projected for 2020, 2055 and 2085.

	Scenario	1990	2020	2055	2085
Australia	Baseline	250	470	500	500
	Low	-	480	520	530
	Medium	-	480	520	540
	High	-	480	530	500
Pacific	Baseline	5140	6080	1850	1210
	Low	-	37600	63200	12400
	Medium	-	39100	69000	43300
	High	-	50300	92300	170000

Table 13. *Estimated number of people (1,000s) exposed to coastal flooding at the baseline year (1990) and three points in the future, under three SLR scenarios, for Australia. Results for the Pacific region are also shown for comparison. Data taken from McMichael et al. (2003) and has been rounded down to three significant figures.*

The study estimated that 250,000 people experience coastal flooding each year in Australia (Australia's current population is 22 million), 100,000 in New Zealand, and 5,140,000 in the Pacific. The baseline scenario (no SLR) projects an increase for Australia to 470,000 people affected in 2020, and 500,000 in 2055 and 2085. These increases relate to the assumed population increase on the coast, and are relatively small compared to the Pacific region as a whole, where the number of people who experience flooding by 2055 could increase by a factor of more than 50, to around 63,000,000-92,000,000 (range across low, medium and high SLR scenarios) in an average year. The relatively small impact of SLR for Australia is due to a decline in population growth from 2050 onwards, and an assumed increase in GDP and an improved adaptive capacity for the region as a whole.

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