EXECUTIVE SUMMARY

INTRODUCTION

This Report provides an assessment of observed climate change in Australia and its causes, and details projected future changes over the 21st century. This document, produced by CSIRO and the Australian Bureau of Meteorology, underpins extensive climate change projections for Australia provided as part of a larger package of products developed with funding from the Commonwealth Government's Regional Natural Resource Management (NRM) Planning for Climate Change Fund.

The projections are based on our understanding of the climate system, historical trends and model simulations of the climate response to global scenarios of greenhouse gas and aerosol emissions. Simulations come from the archive of global climate models (GCMs) developed by modelling groups from around the world through the Coupled Model Intercomparison Project phase 5 (CMIP5) which also underpins the science of the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC).

These projections supersede those released by CSIRO and the Bureau of Meteorology in 2007. Although the findings are similar to those of the 2007 projections, note that these and the 2007 projections are not always directly comparable due to different baselines, emissions scenarios and periods of consideration.

Extensive engagement with users has led to the production of a range of communication tools that support the projections, including guidance material, regional information, animations, webinars, a video and a web site at www.climatechangeinaustralia.gov.au.

Projected changes have been prepared for four Representative Concentration Pathways (RCPs) used by the latest IPCC assessment, which represent different scenarios of emissions of greenhouse gases, aerosols and land-use change. These RCPs include RCP2.6, requiring very strong emission reductions from a peak at around 2020 to reach a carbon dioxide (CO_2) concentration at about 420 parts per million (ppm) by 2100, RCP4.5 with slower emission reductions that stabilise the CO_2 concentration at about 540 ppm by 2100, and RCP8.5 which assumes increases in emissions leading to a CO_2 concentration of about 940 ppm by 2100 (Section 3.2). This range of emissions scenarios is broader than those used for the 2007 projections.

Climate change projections are presented for eight regions (some further sub-divided) covering the entire nation (Section 2.3, Box 2.1).

Confidence ratings for the projections are based on the judgement of the authors derived from multiple lines of evidence. These include physical theory and understanding of processes driving the change, agreement amongst climate model simulations of the future, model evaluation both with respect to current mean climate and recent observed climate change, and consistency of global climate model results with downscaled, high-resolution simulations (Section 6.4).

GLOBAL CHANGES

Global mean near-surface air temperature has risen by around 0.85 °C from 1880 to 2012 and at 0.12 °C per decade since 1951 (Section 3.4 and IPCC). The IPCC (2013) concluded, "It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" and "Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes." Natural forcings (*e.g.* solar variations and volcanic aerosols) and intrinsic climate variability have had little effect on the warming since 1951 (Section 3.4 and IPCC).

Global mean temperatures are projected to rise from 0.3-1.7 °C under RCP2.6 to 2.6-4.8 °C under RCP8.5 by 2081-2100, compared to the climate of 1986-2005 (Section 3.5 and IPCC). Warming is projected to be stronger over land than oceans and strongest over the Arctic (Section 3.5 and IPCC). Hot days and heat waves are projected to become more frequent and cold days less frequent (Section 3.5 and IPCC).

Projected changes in rainfall are much less spatially uniform than projected warming. Rainfall is generally projected to increase at high latitudes and near the equator and decrease in regions of the sub-tropics, although regional changes may differ from this pattern (Section 3.5 and IPCC). Rainfall extremes are projected to become more intense and more frequent in most regions (Section 3.5 and IPCC).

Global mean sea level is projected to increase by 26-55 cm for RCP2.6 and 45-82 cm for RCP8.5 by 2080-2100 relative to 1986-2005 (Section 8.1). Global sea level rise is driven mainly by ocean thermal expansion and melting from glaciers and ice caps.

-20° -10° 0° 10° 20° 30° 40° 50°

AUSTRALIAN CLIMATE VARIABILITY AND CHANGE

AUSTRALIA HAS BEEN WARMING AND WILL WARM SUBSTANTIALLY DURING THE 21ST CENTURY

Australian average surface air temperature has increased by 0.9 °C since 1910, and increasing greenhouse gases have contributed to this rise (Section 4.2.1). Climate models are able to reproduce the observed warming over the 20th century (Sections 5.2, 5.3, 7.1.1).

In recent decades anomalously warm months have occurred more often than anomalously cold months (Section 4.2.1). Many heat-related records were broken in the summer of 2012-13 and in the year of 2013, including Australia's hottest day, week, month and year averaged across Australia (Section 4.2.1). Extreme summer temperatures during 2012-13 were unlikely to have been caused by natural variability alone, and such temperatures are now five times more likely due to the enhanced greenhouse effect (Section 4.2.1).

There is *very high confidence* in continued increases of mean, daily minimum and daily maximum temperatures throughout this century for all regions in Australia. This takes into account the observed warming, strong agreement on the direction and magnitude of change among models, downscaling results and the robust understanding of the driving mechanisms of warming (Section 7.1.1). The magnitude of the warming later in the century is strongly dependent on the emission scenario.

Warming will be large compared to natural variability in the near future (2030) (*high confidence*) and very large compared to natural variability late in the century (2090) under RCP8.5 (*very high confidence*). By 2030 (the period 2020-2039), Australian annual average temperature is projected to increase by 0.6-1.3 °C above the climate of 1986-2005 under RCP4.5 with little difference in warming between RCPs (Section 7.1.1). The projected temperature range by 2090 (the period 2080-2099) shows larger differences between RCPs, with increases of 0.6 to 1.7 °C for RCP2.6, 1.4 to 2.7 °C for RCP4.5 and 2.8 to 5.1 °C for RCP8.5 (Section 7.1.1).

Mean warming is projected to be greater than average in inland Australia, and less in coastal areas, particularly in southern coastal areas in winter (Section 7.1.1).

MORE FREQUENT AND HOTTER HOT DAYS AND FEWER FROST DAYS ARE PROJECTED

Since 2001, the number of extreme heat records in Australia has outnumbered extreme cool records by almost 3 to 1 for daytime maximum temperatures and almost 5 to 1 for night-time minimum temperatures (Section 4.2.1). Heat waves have increased in duration, frequency, and intensity in many parts of the country (Section 4.2.1).

Strong model agreement and our understanding of the physical mechanisms of warming mean that there is *very high confidence* the projected warming will result in more frequent and hotter hot days and warmer cold extremes and *high confidence* in reduced frost. Notably, the projected temperature increase for the hottest day of the year on average and the hottest day in 20 years on average is very similar to the projected increase in mean temperature (Section 7.1.2).

For example, in Perth, the average number of days per year above 35 °C or above 40 °C by 2090 is projected to be 50 % greater than present under median warming for RCP4.5. The number of days above 35 °C in Adelaide also increases by about 50 % by 2090, while the number of days above 40 °C more than doubles (Section 7.1.2).

Locations where frost occurs only a few times a year under current conditions are projected to become nearly frost-free by 2030. Under RCP8.5, coastal areas are projected to be free of frost by 2090 while frost is still projected to occur inland (Section 7.1.2).

MID-LATITUDE WEATHER SYSTEMS ARE PROJECTED TO SHIFT SOUTH IN WINTER AND THE TROPICS TO EXPAND

Observed large-scale circulation changes can be characterised by an expansion of the tropics and a contraction of the mid-latitude storm tracks to higher southern latitudes. Correspondingly, an intensification of the subtropical ridge (the high pressure belt over Australia), an expansion of the Hadley Cell (a circulation in the north-south direction connecting tropical and mid-latitude areas), and a trend to a more positive Southern Annular Mode (a hemispheric mode of variability associated with weaker than normal westerly winds and higher pressures over southern Australia) have all been observed. These changes have been linked to a reduction in rainfall in southern Australia (Section 4.2.3).

The observed intensification of the subtropical ridge and expansion of the Hadley Cell circulation are projected to continue in the 21st century (*high confidence*; Section 7.3.2).

In winter, mid-latitude weather systems are projected to shift south and the westerlies are projected to strengthen (*high confidence*; Section 7.3.2). Concurrent and related changes in the mid-latitude circulation are projected, including a more positive Southern Annular Mode (SAM), a decrease in the number of deep lows affecting south-west Western Australia and a decrease in the number of fronts in southern Australia (Section 7.3.2).

Projected changes to mid-latitude circulation in summer are less clear (Section 7.3.2). There are competing influences, with increasing greenhouse gases leading to a more positive SAM and projected stratospheric ozone recovery leading to a less positive SAM (Section 7.3.2).

Climate models underestimate the observed changes in mid-latitude circulation and southern Australian rainfall (Section 4.2.3). It is unclear whether this is due to natural variability, additional climate influences unaccounted for in the models or due to the models underestimating the true response (Section 4.2.3).

COOL–SEASON RAINFALL IS PROJECTED TO DECLINE IN SOUTHERN AUSTRALIA; OTHER CHANGES TO AVERAGE RAINFALL ARE UNCERTAIN

Australian average rainfall has been increasing since the 1970s, mainly due to an increase in wet season rain in northern Australia (Section 4.2.2). During the cooler months, rainfall has declined in the south-east and south-west of the continent (Section 4.2.2). The rainfall decline in southern Australia has been linked to circulation changes in the southern hemisphere that are influenced by increasing greenhouse gases and reductions in stratospheric ozone (Section 4.2.2).

In southern Australia, cool season (winter and spring) rainfall is projected to decrease (*high confidence*), though increases are projected for Tasmania in winter (*medium confidence*; Section 7.2.1). The cool season rainfall decline is driven by the southward movement of winter storm systems (Section 7.2.1). The winter decline may be as great as 50 % in south-western Australia under RCP8.5 by 2090 (Section 7.2.1). The direction of change in summer and autumn rainfall in southern Australia cannot be reliably projected, but there is *medium confidence* in a decrease in south-western Victoria in autumn and in western Tasmania in summer (Section 7.2.1).

In eastern Australia, there is *high confidence* that in the near future (2030) natural variability will predominate over trends due to greenhouse gas emissions. For late in the century (2090), there is *medium confidence* in a winter rainfall decrease related to the southward movement and weakening of winter storm systems (Section 7.2.1). Otherwise, there is *low confidence* in the direction of seasonal rainfall change due to strongly contrasting results from global climate models and downscaling approaches (Section 7.2.1). The large uncertainty in this region is likely to be related to the range of rainfall drivers and competing influences on rainfall change as well as their relationship to topographical features such as the Great Dividing Range and Eastern Seaboard (Section 7.2.1).

In northern Australia and northern inland areas, there is *high confidence* that in the near future (2030), natural variability will predominate over trends due to greenhouse gas emissions. There is *low confidence* in the direction of future rainfall change by late in the century (2090), but substantial changes to wet-season and annual rainfall cannot be ruled out (Section 7.2.1). Confidence in rainfall projections is low due to the lack of model agreement (Section 7.2.1), and limitations of models in reproducing features of the observed rainfall climate and important drivers of rainfall variability in the region (Section 5.2).

EXTREME RAIN EVENTS ARE PROJECTED TO BECOME MORE INTENSE

Heavy daily rainfall has accounted for an increased proportion of total annual rainfall over an increasing fraction of the Australian continent since the 1970s (Section 4.2.3). Record rainfall totals occurred in many areas during 2010 and 2011, attributable in part to the presence of strong La Niña conditions and higher than average sea surface temperatures to the north of Australia (Section 4.2.2).

Throughout most of Australia, extreme rainfall events (wettest day of the year and wettest day in 20 years) are projected to increase in intensity with *high confidence* due to our understanding of physical mechanisms (increasing moisture-holding capacity of a warmer atmosphere), strong model agreement and a wealth of previous research (Section 7.2.2). However, there is only *medium confidence* in increased rainfall intensity for south-western Western Australia, because of the large projected reduction in mean rainfall in this region (Section 7.2.2).

TIME IN DROUGHT IS PROJECTED TO INCREASE IN SOUTHERN AUSTRALIA, WITH A GREATER FREQUENCY OF SEVERE DROUGHTS

The time in drought, as measured by the Standardised Precipitation Index, is projected to increase over southern Australia with *high confidence* (Section 7.2.3). This is consistent with the projected decline in mean rainfall. Time in drought is projected to increase with *medium* or *low confidence* in other regions. The nature of droughts is also projected to change, with a greater frequency of extreme droughts, and less frequent moderate to severe drought projected for all regions (*medium confidence*) (Section 7.2.3).

SNOWFALL IN THE AUSTRALIAN ALPS IS PROJECTED TO DECREASE, ESPECIALLY AT LOW ELEVATIONS

Average snow depths have decreased at a number of Australian sites since the 1950s. There is *very high confidence* that as warming progresses there will be a decrease in snowfall, an increase in snowmelt and thus reduced snow cover. These trends will be large compared to natural variability and most evident at low elevations (Section 7.2.4).

SMALL CHANGES IN WIND SPEED

Mean wind speeds are projected to decrease in southern mainland Australia in winter and increase in Tasmania

By 2030, changes in near-surface wind speeds are projected to be small compared to natural variability (*high confidence*). By 2090, wind speeds are projected to decrease in southern mainland Australia in winter (*high confidence*) and south-eastern mainland Australia in autumn and spring. Winter decreases are not expected to exceed 10 % under RCP8.5. Wind speed is projected to increase in winter in Tasmania (Section 7.3.1). Projected changes in extreme wind speeds are generally similar to those for mean wind (Section 7.3.1).

TROPICAL CYCLONES MAY OCCUR LESS OFTEN, BECOME MORE INTENSE, AND MAY REACH FURTHER SOUTH

There is some observational evidence for a decrease in the occurrence of tropical cyclones (Sections 4.2.1, 4.2.7). However, the short period of consistent observational records and high year to year variability make it difficult to discern clear trends in tropical cyclone frequency or intensity (Section 4.2.7).

Based on global and regional studies, tropical cyclones are projected to become less frequent with a greater proportion of high intensity storms (stronger winds and greater rainfall) (*medium confidence*). A greater proportion of storms may reach south of latitude 25 degrees South (*low confidence*; Section 7.3.2).

MORE SUNSHINE IS PROJECTED IN WINTER AND SPRING, WITH LOWER RELATIVE HUMIDITY AND HIGHER EVAPORATION RATES THROUGHOUT THE YEAR

There is *high confidence* in little change in solar radiation over Australia in the near future (2030). Late in the century (2090), there is *medium confidence* in an increase in winter and spring in southern Australia (Section 7.4). The increases in southern Australia may exceed 10 % by 2090 under RCP8.5 (Section 7.4).

Relative humidity is projected to decline in inland regions and where rainfall is projected to decline (Section 7.5). By 2030, the decreases are relatively small (*high confidence*). By 2090, there is *high confidence* that humidity will decrease in winter and spring as well as annually, and there is *medium confidence* in declining relative humidity in summer and autumn (Section 7.5).

There is *high confidence* in increasing potential evapotranspiration (atmospheric moisture demand) closely related to local warming, although there is only *medium confidence* in the magnitude of change (Section 7.6).

SOIL MOISTURE IS PROJECTED TO DECREASE AND FUTURE RUNOFF WILL DECREASE WHERE RAINFALL IS PROJECTED TO DECREASE

Soil moisture and runoff projections are strongly influenced by projected changes in rainfall (Sections 7.7.1, 7.7.2), but tend toward decrease because of projected increases in potential evapotranspiration. Changes in runoff are generally 2-3 times larger than the relevant rainfall change (Section 7.7.2).

There is *high confidence* in decreasing soil moisture in the southern regions (particularly in winter and spring) driven by the projected decrease in rainfall and higher evaporative demand (Section 7.7.1). There is *medium confidence* in decreasing soil moisture elsewhere in Australia where evaporative demand is projected to increase but the direction of rainfall change in uncertain (Section 7.7.1).

Decreases in runoff are projected with *high confidence* only in south-western Western Australia and southern South Australia, and with *medium confidence* in far south-eastern Australia, where future rainfall is projected to decrease. The direction of change in future runoff in the northern half of Australia cannot be reliably projected because of the uncertainty in the direction of rainfall change (Section 7.7.2).

SOUTHERN AND EASTERN AUSTRALIA ARE PROJECTED TO EXPERIENCE HARSHER FIRE WEATHER; CHANGES ELSEWHERE ARE LESS CERTAIN

Extreme fire weather days have increased at 24 out of 38 Australian sites from 1973-2010, due to warmer and drier conditions.

Projected warming and drying in southern and eastern Australia will lead to fuels that are drier and more ready-to-burn, with increases in the average forest fire danger index and a greater number of days with severe fire danger (*high confidence*; Section 7.8).

In northern Australia and inland areas, the primary determinant of bushfires is fuel availability, which depends strongly on year to year rainfall variability (Section 7.8). There is *medium confidence* that there will be little change in fire frequency in tropical and monsoonal northern Australia. There is *low confidence* in projections of fire risk in the arid inland areas where fire risk is dependent on availability of fuel, which is driven by episodic rainfall.

SEA LEVELS WILL CONTINUE TO RISE THROUGHOUT THE 21ST CENTURY AND BEYOND; EXTREME SEA LEVELS WILL ALSO RISE

For 1966 to 2009, the average rate of relative sea level rise from observations along the Australian coast was 1.4 ± 0.2 mm/year, and 1.6 ± 0.2 mm/year when the sea level variations directly correlated with the Southern Oscillation Index (SOI) are removed (Section 8.1.3).

In line with global mean sea level, Australian sea levels are projected to rise through the 21st century (*very high confidence*), and are very likely to rise at a faster rate during the 21st century than over the past four decades, or the 20th century as a whole, for the range of RCPs considered (*high confidence*). Sea level projections for the Australian coastline by 2090 (the average of 2080 to 2100) are comparable to, or slightly larger than (by up to about 6 cm) the global mean sea level projections of 26-55 cm for RCP2.6 and 45-82 cm for RCP8.5 (*medium confidence*; Section 8.1.5). These ranges of sea level rise are considered likely (at least 66 % probability), and if a collapse in the marine based sectors of the Antarctic ice sheet were initiated, the projections could be up to several tenths of a metre higher by late in the century. Regional projections for 2100 (a single year) are not given because of the effect of interannual to decadal variability on regional sea levels. However, for all scenarios, global averaged sea level in 2100 will be higher than in 2090 and sea level is projected to continue to rise beyond 2100.

Taking into account uncertainty in sea level rise projections and the nature of extreme sea levels along the Australian coastline, an indicative extreme sea level 'allowance' is calculated. This allowance is the minimum distance required to raise an asset to maintain current frequency of breaches under projected sea level rise. Along the Australian coast, these allowances are comparable to the upper end of the range of the respective sea level projections (*medium confidence*; Section 8.2). The main contribution to increasing extreme sea levels is from the rise in mean sea level (*medium confidence*). Contributions to extreme sea levels from changes in weather events are projected to be small or negative (*low confidence*; Section 8.2).

OCEANS AROUND AUSTRALIA WILL WARM AND BECOME MORE ACIDIC. SALINITY MAY ALSO CHANGE

There is *very high confidence* that sea surface temperatures around Australia will rise, with the magnitude of the warming dependent on the RCP (Section 8.3). Near-coastal sea surface temperature rise around Australia is typically around 0.4-1.0 °C by 2030 and around 2-4 °C by 2090 under RCP8.5 compared to current (1986-2005) (Section 8.3).

Changes in sea surface salinity reflect changes in rainfall (Section 7.2) and may affect ocean circulation and mixing. A net reduction in the salinity of Australian coastal waters is projected, but this projection is of *low confidence* (Section 8.4). For some southern regions, models indicate an increase in sea surface salinity, particularly under higher emissions (Section 8.4).

The oceans are absorbing more than 25 % of current carbon dioxide emissions (Section 8.5). In the oceans, carbon dioxide dissolves and leads to a reduction in carbonate concentration and seawater pH. This is known as ocean acidification (Section 8.5). There is *very high confidence* that around Australia the ocean will become more acidic, with a net reduction in pH (Section 8.5). There is also *high confidence* that the rate of ocean acidification will be proportional to carbon dioxide emissions (Section 8.5). There is *medium confidence* that long-term viability of corals will be impacted under RCP8.5 and RCP4.5, and that there will be harm to marine ecosystems from the projected reduction in pH under RCP8.5 (Section 8.5).

MODEL EVALUATION AND PROJECTION METHODS

The climate models used for making future climate projections were evaluated by examining their simulation of the present climate of the Australian region (Chapter 5). This evaluation contributes to assessment of confidence in model-simulated future climate changes (see Chapter 6, Section 6.4) and to assessment of the adequacy of any model or models for particular applications.

The ability of individual CMIP5 models to simulate Australian climate depends on the climatic variable, region and season under consideration. Observed climate for broad-scale temperature, rainfall and surface wind is well captured by global climate models, although deficiencies are found in finer details around pronounced topography and coastlines such as in Tasmania or the Cape York Peninsula (Sections 5.2).

Global climate models are also able to reproduce the major climate systems, including sources of year to year variability, which affect Australia. However, there are deficiencies in simulating aspects of the El Niño – Southern Oscillation (ENSO) and its connection to Australian rainfall. Some models also do not simulate monsoon onset well (Section 5.2.4).

The projections presented here are based on all the available simulations since no subset of climate models was found to perform well across all metrics, and methods that did allow for model performance did not lead to different projection results (Section 6.2). However, information about consistently poorly performing models is used in model selection for some more specific applications (Sections 9.2.3, 9.3.4, Box 9.1).

Projections are presented as ranges of change for different 20-year time periods in the future with respect to the reference period (1986–2005). Generally, the 10th to 90th percentile range of the distribution of CMIP5 global climate model results is used to characterise the projections (Section 6.2.2).

In addition, time series of simulated climate change from 1910 to 2090 against a 1950 to 2005 baseline are shown together with observations to illustrate the interplay of the slowly emerging climate change signal and natural internal variability (Section 6.2.2, Box 6.2.2).

USING CLIMATE CHANGE DATA IN IMPACT ASSESSMENT AND ADAPTATION PLANNING

Climate change data provide an essential input to the impact assessment process (Section 9.2). The framework for impact assessment includes context setting, impact identification and impact analysis, the latter incorporating consideration of planning horizons and relevant climate data input. Methods for generating, presenting and selecting data are described, along with information to help users find data and research tools on the Climate Change in Australia website (Section 9.3). This website includes a decision tree to guide users to the most relevant material; report-ready images and tables; climate change data (described as, for example, a 10 percent decrease in rainfall relative to 1986-2005); and application-ready data (where projected changes have been applied to observed data for use in detailed risk assessments) (Section 9.3.4). Links are also provided to other projects that supply climate change information (Section 9.3.6).