Climate Change Impacts on Australia and the Benefits of Early Action to Reduce Global Greenhouse Gas Emissions

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EXECUTIVE SUMMARY

Australia is one of the many global regions experiencing significant climate change as a result of global emissions of greenhouse gases (GHGs) from human activities. The average surface air temperature of Australia increased by 0.7°C over the past century – warming that has been accompanied by marked declines in regional precipitation, particularly along the east and west coasts of the continent. These seemingly small changes have already had widespread consequences for Australia. Unfortunately, even if all GHG emissions ceased today, the Earth would still be committed to an additional warming of 0.2–1.0°C by the end of the century.

Yet the momentum of the world's fossil fuel economy precludes the elimination of GHG emissions over the near-term, and thus future global warming is likely to be well above 1°C. Analysis of future emissions trajectories indicates that, left unchecked, human GHG emissions will increase several fold over the 21st century. As a consequence, Australia's annual average temperatures are projected to increase 0.4–2.0°C above 1990 levels by the year 2030, and 1–6°C by 2070. Average precipitation in southwest and southeast Australia is projected to decline further in future decades, while regions such as the northwest may experience increases in precipitation. Meanwhile, Australia's coastlines will experience erosion and inundation from an estimated 8–88 cm increase in global sea level.

Such changes in climate will have diverse implications for Australia's environment, economy, and public health. The biodiversity, ecosystems, and natural habitats of Australia are world renowned, yet potentially the most fragile of the systems that will be exposed to climate change. For example, the Great Barrier Reef, a UNCESCO World Heritage area, has experienced unprecedented rates of bleaching over the past two decades, and additional warming of only 1°C is anticipated to cause considerable losses or contractions of species associated with coral communities.

Australian crop agriculture and forestry may experience transient benefits from longer growing seasons a warmer climate and increasing atmospheric CO_2 concentrations, yet such benefits are unlikely to be sustained under the more extreme projections of global warming. Furthermore, changes in precipitation and subsequent water management are critical factors affecting the future productivity of the Australian landscape. The declines in precipitation projected over much of Australia will exacerbate existing challenges to water availability and quality for agriculture as well as for commercial and residential uses.

Future changes in climate extremes, such as tropical cyclones, heat waves, and extreme precipitation events, would degrade Australian infrastructure and public health; e.g. through increased energy demands, maintenance costs for transportation infrastructure, and coastal flooding. Global large-scale singularities, such as a slowing or collapse of the ocean's thermohaline circulation or the collapse of the ice sheets of West Antarctica or Greenland, would also have important long-term implications for Australia's climate and coastline.

Avoiding, or at the very least reducing, the adverse effects of climate change is a global challenge, yet one that will generate direct benefits for species and habitat conservation, saved lives, and reduced economic and infrastructure costs. For example, limiting future increases in atmospheric CO_2 to 550 ppmv, though not a panacea for global warming, would reduce 21st century global warming to an estimated 1.5–2.9°C, effectively avoiding the more extreme climate changes. Lower stabilisation levels, such as 450 ppmv CO_2, would reduce future warming even further, to approximately 1.2–2.3°C. For Australia, such constraints on global warming would give natural ecosystems and their associated species greater time to adapt to changing environmental conditions, reduce the likelihood of major adverse consequences for agriculture and forestry, help ensure Australia's public health infrastructure can keep pace with emerging health challenges, and reduce the chance of large-scale singularities. Nevertheless, even with a return to 350 ppmv as the stabilisation level, the Earth will not be able to avoid its current commitment to additional future warming. Therefore, prudence dictates that GHG mitigation activities be pursued in conjunction with adaptive responses to address the residual risks posed by this commitment.

There is broad, and growing, international support for GHG mitigation. The 1992 United Nation's Framework Convention on Climate Change, supported by 166 nations, calls for the "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*." A number of national governments and climate scientists have suggested atmospheric CO_2 concentrations between 375 and 550 ppmv and/or temperature increases of 0.9–2.9°C above 1990 levels as global thresholds for "dangerous" climate change.

Although a specific long-term stabilisation target has not been adopted by the UNFCCC, several national governments, including the United Kingdom and Sweden, have committed to GHG emissions reductions of 60% by the year 2050, a general benchmark estimate of the effort needed by developed, Annex I countries to place the world on a path to achieving a global stabilisation level of no more than 550 ppmv. Similar targets have been explored or recommended by institutions in the United States, the European Union, and recently in Australia, by New South Wales' *Greenhouse Advisory Panel*. This technical report outlines the likely impacts on Australia of climate change, and the benefits of global emissions reductions.

1. THE CHANGING GLOBAL CLIMATE

Over the 20th century, average air temperatures at the Earth's surface increased by approximately 0.6°C (IPCC, 2001; **Figure 1**).[1] The 1990s were the warmest decade since the beginning of instrumental records, and various proxy studies have indicated that temperatures in the northern hemisphere at the end of the 20th century were warmer than at any point in the past 1–2 thousand years.[2] These temperature increases have also influenced the global hydrological cycle. Precipitation in the northern hemisphere increased 5–10% over the 20th century, with most of this increase manifesting as extreme rainfall events.[1] These global changes have been mirrored in Australia, where average temperatures have increased by about 0.7°C since 1910.[3] Precipitation in Western Australia and along Australia's east coast has declined steadily since the mid-20th century, while precipitation has increased in the northwest.[3] Australia has also experienced an increase in extreme rainfall events, particularly during winter.

These observed changes in global and regional climates have been attributed in part to human emissions of greenhouse gases (GHGs) since the industrial revolution. Atmospheric concentrations of carbon dioxide have increased by over 30% (from 280 to 380 parts per million), while concentrations of nitrous oxide and methane have increased by 17% and 151%, respectively.[1] These changes in the composition of the atmosphere alter the radiative balance of the Earth – the balance between incoming solar radiation and outgoing heat. Greenhouse gases reduce the radiation of heat from Earth's atmosphere into space, trapping more heat in the atmosphere, and thus increasing global temperatures. These changes in Earth's radiative balance explain a significant fraction of the observed changes in global as well as Australia's climate, even after considering other important climate drivers such as solar variability and volcanic aerosol emissions.[4,5]

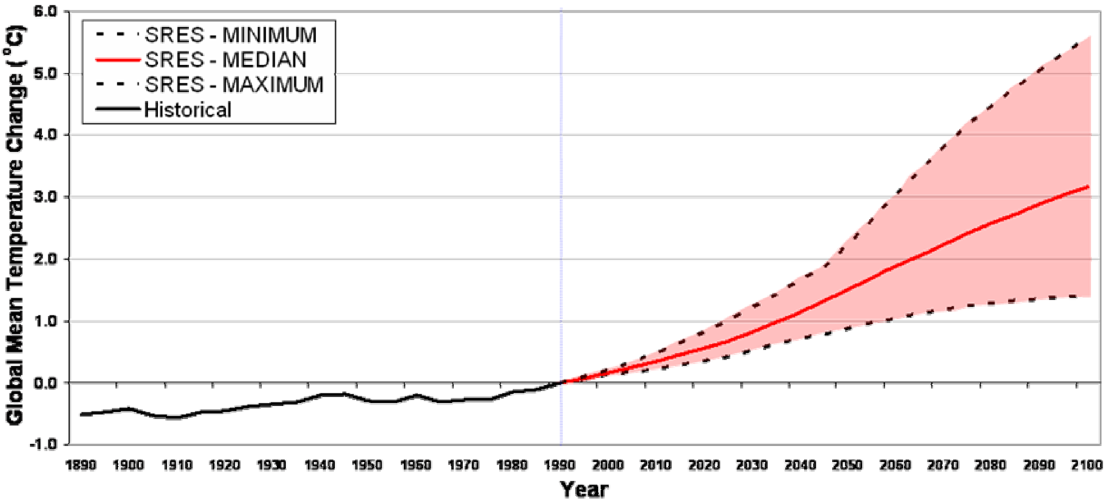

Figure 1. *Projections of 21st century temperature increases (relative to 1990) from the MAGICC (v.4.2) simple climate model tuned to seven different global climate models with climate sensitivities ranging from 1.7-4.2°C. The lower and upper bounds represent the minimum warming resulting from the SRES B1 scenario and the maximum warming from the SRES A1C scenario, respectively, for the seven climate models. The median estimate is based on an emissions scenario representing median emissions from the full range of SRES scenarios. Historical temperature anomalies are based upon a 5-year moving average of the NASA Goddard Institute for Space Studies analysis, normalised to 1990.*

Human emissions of GHGs are projected to increase further in the decades ahead. The Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES) projected a range of CO_2 emissions of 3.3 to 36.8 GtC/year by 2100 relative to 1990 levels of 7.1 GtC/year.[6] These emissions will drive further increases in the atmospheric concentration of CO_2 and other GHGs, further altering the global climate. The IPCC projects global mean temperatures will increase by 1.4–5.8°C above 1990 levels by 2100 (**Figure 1**), accompanied by an increase in sea level of 8–88cm.[1] These projections are in addition to the approximate 0.6°C of warming and 10–20 cm of sea-level rise that occurred over the 20th century, prior to 1990 (**Figure 1**). Unchecked, global warming will not cease in 2100, but continue into subsequent centuries. All projected changes in climate referred to in this report, such as changes in temperature, are relative to 1990 unless otherwise stated.

Over most of Australia, annual average temperatures are projected to increase by 0.4−2.0°C from 1990 levels by the year 2030 and by 1−6°C by 2070 (**Figure 2**).[3] Inland areas are likely to warm faster than the global average, while coastal areas and the tropics will warm at around the global average. The average number of days over 35°C may rise 10−100% by 2030 while the average number of days below 0°C may fall 20−80%. Annual average rainfall may tend to decrease in the southwest and in the southeast. In other areas, including parts of eastern Australia, projected rainfall changes are uncertain. Where average rainfall increases, there is likely to be more extremely wet years, and where average rainfall decreases more droughts are anticipated.

Some degree of additional climate change is now inevitable. If one assumes that atmospheric composition was held constant at today's levels, the Earth would still be committed to an additional warming of 0.2–1.0°C by the end of the century, or 2.0–5.5°C at climate equilibrium.[7] This highlights the inertia of the climate system and, given the further increases in

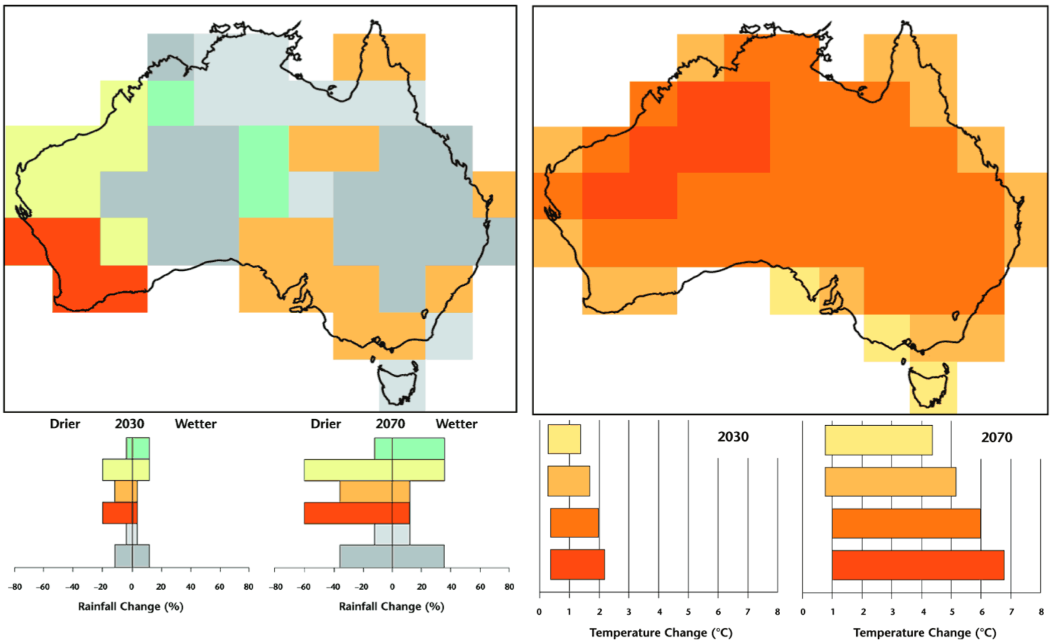

Figure 2. *Spatial distribution of projected changes in Australian precipitation (left) and temperature (right) in 2030 and 2070.*

emissions projected, indicates the challenge and importance of reducing global emissions of GHGs if one is to ensure that large additional changes in the climate system are avoided. This report summarizes current international efforts to define and achieve an appropriate stabilisation target, the principle considerations in achieving emissions reductions toward a stabilisation of atmospheric concentrations of GHGs, and the potential impacts to Australia from a range of future changes in global and Australian climate.

2. THE EMERGING CONSENSUS ON GREENHOUSE GAS STABILISATION

The United Nations Framework Convention on Climate Change (UNFCCC) emerged from the Rio Earth Summit in 1992. The UNFCCC established an international framework for addressing the global challenge of anthropogenic climate change. The text of the convention was adopted in 1992 and within the following year was signed by 166 countries. The objective of the convention is specified by Article II:

> "*The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention,* ***stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system****. Such a level should be achieved within a time-frame sufficient to allow*

ecosystems to adapt naturally to climate change, ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." [8]

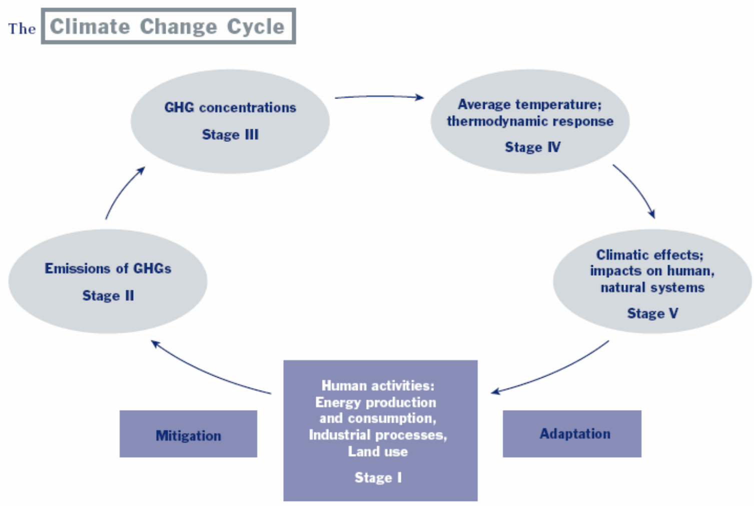

Figure 3. *Chain of processes leading from human activities (Stage I) to climate impacts (Stage V).*

Article II expresses "dangerous anthropogenic interference (DAI)" in terms of impacts, particularly to ecosystems, food production, and economies. However, Article II does not define the precise nature and magnitude of impacts to these systems that one should consider dangerous. Furthermore, climate impacts are the outcome of a chain of processes (**Figure 3**), which begin with human activities (Stage I).[9] Transportation, power generation, industry, and land use contribute to GHG emissions (Stage II), which build up in the atmosphere (Stage III). Changes in the atmospheric composition alter global patterns of temperature, precipitation, and sea level (Stage IV), which result in climate impacts to human and natural systems (Stage V).

Prevention or amelioration of climate impacts can be accomplished through two different processes: *adaptation* and *mitigation*. Through adaptation, one reduces the magnitude of the consequences associated with a particular magnitude of climate change. Adaptation measures are generally implemented at the local level and reduce risk from the bottom-up. Meanwhile, mitigation reduces emissions of GHGs from human activities, thereby reducing the magnitude of climate change to which human and natural systems are exposed. Unlike adaptation, mitigation is largely top-down in at least two senses. First, the effects of mitigation are largely felt at the global level in terms of the avoided changes in global climate. Second, the political organization of mitigation efforts to date has largely been top-down in focus, involving international, national, and state-level governance.

As specified in Article II, the UNCCC focuses risk management efforts on mitigation to "*stabilise greenhouse gases in the atmosphere*" (Stage III). Determining the appropriate level of stabilisation necessitates working backwards from impacts to climatic changes and then to stabilisation, using so-called inverse, or diagnostic, approaches. Unfortunately, this is not a straightforward task, primarily due to uncertainty in climate sensitivity (the change in global mean temperature from a doubling of the preindustrial concentration of atmospheric CO_2) and uncertainties in the response of natural and humans systems to those climate changes.

Various attempts at this type of assessment have been made in order to define the global mean temperature change and/or stabilisation level consistent with Article II's concept of DAI (**Table 1**). Most of these attempts have applied the precautionary principle (e.g. UNFCCC calls for "precautionary measures"), where lack of scientific certainty should not be used to prevent or delay action.[8] These attempts have yielded stabilisation targets ranging from 375–550 ppmv, with temperature targets ranging from 0.9–2.9°C above 1990 levels.

Thresholds for DAI establish long-term targets which can be used to guide mitigation efforts. Yet ultimately, because the concentration of CO_2 in the atmosphere is the result of human activities that emit GHGs, determining the effort required to achieve a particular stabilisation or climate target necessitates working backwards from those targets to establish sustainable levels of emissions required to meet those targets. Once again, such inverse modelling gives rise to another set of uncertainties. Estimating future global emissions and the potential for emissions reduction is hampered by uncertainties in future economic growth (globally and regionally) as well as the rate of technological innovation and change. Despite these challenges, there are a number of arguments in favour of pursuing long-term mitigation targets. According to Pershing and Tudela (2003),[9] such targets are useful for

- *Providing a concrete goal for current and future climate efforts*
- *Increasing awareness of the long-term consequences of our actions*
- *Calibrating short-term measures and measuring progress*
- *Inducing technological change*
- *Limiting future risks derived from climate change*
- *Mobilizing society*
- *Promoting global participation*

Because of these benefits, a number of efforts have been launched at the national and international level to establish long-term stabilisation goals. The European Union, the UK, and Sweden for example, have all embraced a stabilisation target of 550 ppmv (**Table 1**), and various strategies are being developed in pursuance of this target. These efforts are indicative of growing commitments among developed countries toward achieving national contributions to global GHG emissions reductions and, ultimately, atmospheric stabilisation.

If a policy target is selected, strategies should be developed to achieve emissions reductions consistent with that target. The Kyoto Protocol to the UNFCCC was ratified in February of 2005 and outlines a legal framework in pursuance of short-term global emissions reductions as a first step toward atmospheric GHG stabilisation. The individual targets for the Annex I members of the Kyoto Protocol add up to a total cut in greenhouse-gas emissions of ~5% for Annex I countries from 1990 levels by the commitment period 2008–2012. The mechanism that the UNFCCC will pursue to achieve further emissions reductions beyond 2012 is currently under discussion. A long-term target has not been selected, but additional and substantial post-2012 emissions reductions are recognized to be necessary if any stabilisation target is to be achieved. Australia has chosen to not ratify the Kyoto Protocol, yet remains committed to achieving Kyoto-like emissions growth targets via a range of measures within its *Greenhouse Gas Abatement Program*.[10] Furthermore, the Kyoto Protocol is but one of a broad range of potential strategies for addressing climate change currently being discussed, recommended, or implemented across geographic and political scales.[11]

Table 1. *Proposed temperature and/or CO_2 concentration thresholds for "dangerous anthropogenic interference".*

Source	Global Mean Temperature Change (°C)[a]	Atmospheric CO_2 Stabilisation Level (ppmv)	Non-CO_2 Gases?[b]
Azar and Rodhe (1997)[12]	1.4	375	
Climate Options for the Long-Term (2002)[13]	1.5	450	
Climate Taskforce (2005)[14]	1.4	400	●
Environmental Systems Analysis Group (2005)[15]	0.9		
European Climate Forum (2004)[16]	1.9[c]		
European Union (1996)[17]	1.4	550	
Hansen et al. (2005)[18]	1.0	475	
Klimatkommittén (2000)[19]		550	●
Mastrandrea and Schneider (2004)[20]	2.9[d]		
O'Neill and Oppenheimer (2002)[21]	2.0	450	
Rijsberman and Swart (1990)[22]	1.4		
Royal Commission on Environmental Pollution (2003)[23]		550	
Wissenschaftlicher Beirat der Bundesregierung (1995)[24]	1.3		
Wissenschaftlicher Beirat der Bundesregierung (2003)[25]	1.4		
Average	**1.5**	**475**	

[a]Relative to 1990, assuming 0.6°C of warming occurred between the industrial revolution and 1990
[b]Stabilisation targets include non-CO_2 gases on a CO_2-equivalent basis
[c]"Critical limits" estimated as 1.4-2.5°C; midpoint of this range used here
[d]Median estimate of the threshold for "dangerous anthropogenic interference"

3. ACHIEVING STABILISATION OF GREENHOUSE GASES

The principle behind GHG stabilisation is conceptually quite simple: to maintain a stable level of CO_2 in the atmosphere, emissions of CO_2 from natural and human sources must equal removals. The natural sources and sinks for CO_2 have varied widely during past glacial and interglacial cycles but have remained below 300 ppmv for at least 420,000 years.[26] With the industrial revolution, humans began transferring carbon that was effectively locked away in the Earth's crust to the atmosphere, upsetting the balance of the carbon cycle. The natural sinks for carbon (primarily terrestrial vegetation and oceans) currently sequester ~40% of emissions from fossil fuel sources.[27] The remaining 60% remains in the atmosphere. As a result, atmospheric CO_2 concentrations have increased from 280 ppmv at the start of the industrial revolution to their current concentration of over 370 ppmv.[28] The current rate of atmospheric CO_2 accumulation (~1.8 ppmv/year) is approximately 2–3 times that of the early 1960s.

Achieving stabilisation means reducing global emissions of CO_2 to a level that prevents any net accumulation of CO_2 in the atmosphere. This means either returning the carbon cycle to its natural (interglacial) state or identifying additional pathways for removing and sequestering atmospheric carbon (e.g., terrestrial or geologic sequestration).

To understand the challenge associated with stabilising atmospheric CO_2, it helps to examine projections of future global GHG emissions. The IPCC Special Report on Emissions Scenarios (SRES) presented a series of emissions scenarios based upon different assumptions about future economic, technological, and social changes without specific policies to reduce GHG emissions.[29] Emissions in 2050 and 2100 for the six "illustrative" SRES scenarios are listed in **Table 2**, while a time series for these scenarios appears in **Figure 4**. All of these scenarios suggest that emissions will be at least 2–4 times 1990 levels by 2050, and may be as high as 5 times 1990 levels by 2100. Thus, substantial increases in GHG emissions over the 21st century are anticipated by most emission scenarios. Only two scenarios (A1T and B1) show emissions declining below 1990 levels by the end of the century.

In addition, the distribution of emissions over time can have a significant influence on the climate. For example, the SRES A1T scenario has higher emissions than the B2 scenario in 2050, yet beyond 2050 A1T emissions decline significantly, while B2 emissions continue to grow. As a result, by 2100, annual B2 emissions are approximately three-fold higher than those of B2. Yet, the projected range of temperature change in 2100 for the A1T scenario remains higher than that of B2. This is a function of two factors. First, due to high near-term emissions, the cumulative emissions of A1T are only marginally lower than those of B2 (**Table 2**), despite a large reduction in emissions post 2050. In other words, the benefits of emission reductions in the second-half of the 20th century are offset by large emissions during the first half. Second, A1Ts high near-term emissions also put significant global warming in the pipeline, resulting in a more rapid rate of warming.

Regardless of the assumptions about future "business-as-usual" trajectories for GHG emissions, it is clear that achieving no net growth in atmospheric concentrations requires reversing the current trend of increasing GHG emissions – ultimately reducing emissions to levels well below those of 1990. It is possible to estimate the allowable emissions that enable the eventual stabilisation of GHGs. For example, the Wigley, Richels, Edmonds (WRE) stabilisation scenarios represent theoretical emissions pathways that result in a range of stabilisation levels from 350 to 1,000 ppmv (**Table 2**; **Figure 5**).[30] These various scenarios assume CO_2 continues to accumulate in the atmosphere until between 2090 (for a 450 ppmv target) and 2375 (for a 1,000 ppmv target). The emissions pathways that result in these stabilisation levels vary significantly. For a 450 ppmv target, emissions continue to increase to a peak of ~11 GtC/year

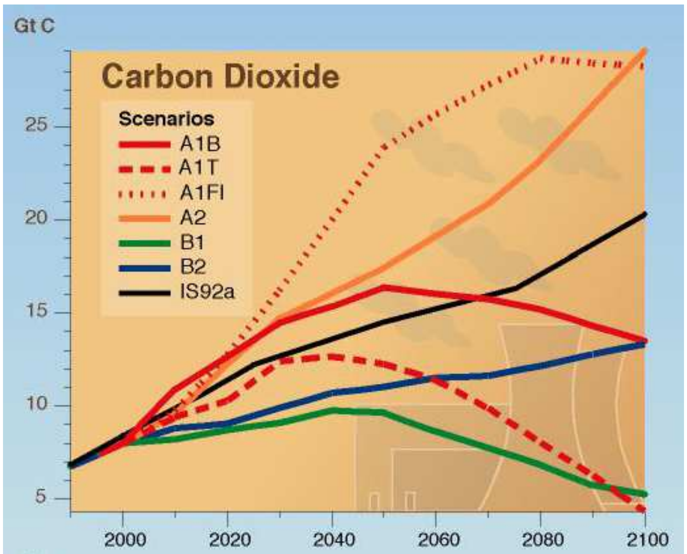

Figure 4. *Twenty-first century carbon dioxide emissions for the SRES scenarios.*

in 2015, after which emissions decline progressively until they are a fraction of 1990 emissions. For higher stabilisation levels, emissions peak at a later date and a higher magnitude before subsequently declining.

Table 2. *Projected emissions and global mean temperature changes associated with the IPCCs SRES scenarios and the WRE stabilisation scenarios. 1990 emissions are presented as a reference point.*[31]

Emissions Scenarios	CO_2 Emissions ($Gt\ C\ yr^{-1}$)		Cumulative CO_2 Emissions (Gt C)	Year of Stabilis-ation	Global ΔT (2100)	Global ΔT (2300)
1990	7.1					
SRES						
	2050	**2100**	**2001-2100**			
A1B	16.4	13.5	1,415		2.1 – 3.8	
A1T	12.3	4.3	985		2.7 – 3.3	
A1FI	23.9	28.2	2,105		3.2 – 5.8	
A2	17.4	29.1	1,780		2.8 – 4.7	
B1	11.3	4.2	900		1.4 – 2.6	
B2	11.0	13.3	1,080		1.9 – 2.5	
WRE						
	2050	**2100**	**2001-2100**			
450	3.0 – 6.9	1.0 – 3.7	365 – 735	2090	1.2 – 2.3	1.5 – 2.9
550	6.4 – 12.6	2.7 – 7.7	590 – 1,135	2150	1.5 – 2.9	1.8 – 3.8
650	8.1 – 15.3	4.8 – 11.7	735 – 1,370	2200	1.7 – 3.2	2.2 – 4.6
750	8.9 – 16.4	6.6 – 14.6	820 – 1,500	2250	1.8 – 3.3	2.6 – 5.2
1,000	9.5 – 17.2	9.1 – 18.4	905 – 1,620	2375	2.0 – 3.5	3.1 – 6.3

The various WRE scenarios generally constrain future changes in global mean temperature to varying degrees (**Table 2**; **Figure 5**). A 450 ppmv stabilisation target lowers warming by 2100 to 1.2–2.3°C, relative to the 1.4–5.8°C projected from the SRES scenarios with no mitigation (**Table 1**). The 1,000 ppmv target lowers warming to 2.0–3.5°C by 2100. Notice that uncertainties among the various stages in the climate change cycle (**Figure 3**) means that the temperatures associated with a particular stabilisation cannot be known with exactness. Instead, the assumption of stabilisation only constrains the uncertainty in future temperature change to a smaller range, and there is considerable overlap in temperature ranges among different stabilisation levels (**Table 2**). In addition, these temperature ranges suggest there is a built-in commitment to additional warming on the order of ~1°C that exists largely independent of mitigation efforts.[7]

It is also important to note that warming continues beyond 2100 for all of the stabilisation scenarios (**Table 2**), and thus stabilisation of the climate (i.e., temperatures) lags considerably behind stabilisation of atmospheric GHG concentrations. This is due to two reasons: a) several of the scenarios don't achieve stabilisation until post-2100 (**Table 2**), and b) it takes centuries for the climate system to reach equilibrium with atmospheric GHG levels. Thus, the ultimate magnitude of temperature change associated with a given stabilisation level may be 25–50% higher than 2100 levels.

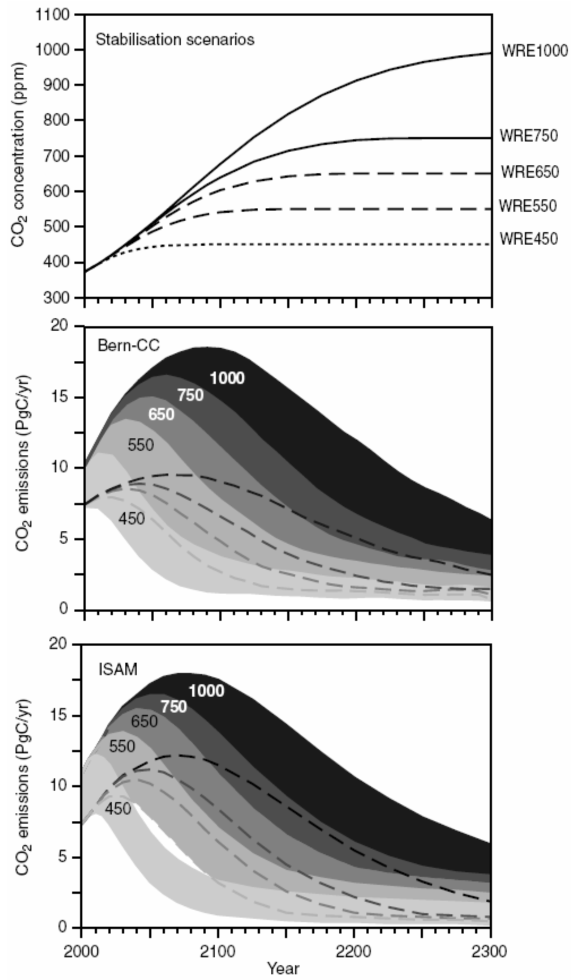

Figure 5. *Temporal evolution of atmospheric concentrations associated with the WRE stabilisation scenarios (top) and the associated emissions pathways based upon two carbon cycle models (BERN-CC and ISAM).*

The WRE scenarios represent just one set of potential pathways leading to GHG stabilisation. In reality, there are effectively an infinite number of pathways that lead to GHG stabilisation. In essence, achieving a particular stabilisation target is equivalent to placing a cap on net emissions between the present and the time of stabilisation. Such a cap effectively creates a GHG "budget", representing the net allowable emissions. Although the budget for a particular stabilisation level is fixed (subject to the availability of sources for sequestration), the emissions can be allocated over a diverse array of pathways. Yet some pathways may be more or less politically, economically, and technologically feasible than others. Delaying action to reduce emissions, for example, allows emissions to continue to grow at a relatively rapid rate over the near term, but requires more abrupt and potentially costly actions at a later date to achieve a given stabilisation target. Furthermore, delayed emissions reductions or temporary overshoots of a stabilisation target tend to result in more rapid warming.[32] Therefore, if the goal of achieving a particular stabilisation target is to avoid specific magnitudes and/or rates of warming, sea-level rise, and downstream impacts, early action to reduce near-term emissions may be a more robust strategy than delay.

Another important consideration in GHG stabilisation is the role of non-CO_2 gases (e.g., methane, nitrous oxide). The WRE stabilisation scenarios focus primarily on CO_2 and generally assume that non-CO_2 gases continue to grow along business-as-usual trajectories.[33] Although the radiative forcing of these gases is low relative to CO_2, different assumptions about future trends in these gases can have a significant influence on the range of temperature changes associated with a particular stabilisation scenario.[33,34] Thus, it may be more relevant to consider CO_2-equivalent (CO_2e) stabilisation levels, which reflect the radiative effects of all GHGs normalized to the radiative forcing of CO_2. This is particularly relevant if one is attempting to limit future climate change to a particular magnitude of global warming. For example, according to Hansen and Sato (2004), limiting future warming to 1°C requires a CO_2 stabilisation level of 520 ppmv if effort is focused on reducing CO_2 and non-CO_2 gases in unison, but 440 ppmv if the non-CO_2 gases are neglected.[34] Focus on the non-CO_2 gases also enables greater flexibility in addressing CO_2 emissions. Non-CO_2 gases can likely be reduced at a lower cost, at least initially, than CO_2. Thus, the greater the contribution of non-CO_2 gas emissions reductions to achieving a particular CO_2 target, the lesser the burden on CO_2.[35]

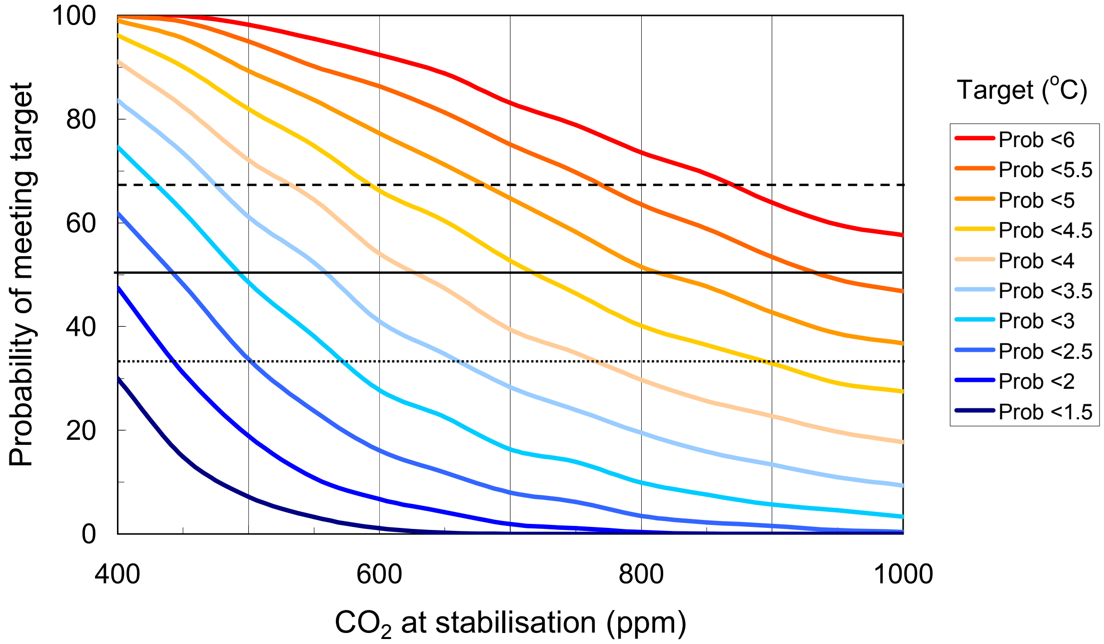

Figure 6. *Probabilities (expressed as a percent) of remaining below a range of targets for global mean temperature change (at the time of stabilisation) given different atmospheric CO_2 stabilisation levels and assuming a climate sensitivity range of 1.5-4.5°C.*

Given that the goal of achieving GHG stabilisation is to remain below the threshold for DAI, it helps to consider the likelihood of exceeding a particular climate threshold given a certain stabilisation level. **Figure 6** presents the probability of remaining below a range of thresholds for global mean temperature change (at the time of stabilisation; see **Table 2**) given a range of CO_2 atmospheric stabilisation levels.[36] The more stringent the climate threshold, the lower the stabilisation level must be in order to have confidence in remaining below that threshold. For example, one has a probability of almost 50% of remaining below 2°C for a stabilisation level of 400 ppmv. This probability decreases for higher stabilisation levels until approximately 600 ppmv, at which point the likelihood of remaining below 2°C is effectively negligible. In contrast, temperature targets of 5–6°C likely can be met with relatively liberal stabilisation levels (i.e., 800–1,000 ppmv). Given a magnitude of climate change to be avoided and a level of acceptable risk, it is possible to identify an appropriate stabilisation level.

Alternatively, given the inherent uncertainties associated with the climate response to a given stabilisation level, choosing a fixed concentration target which is maintained in perpetuity may not be a particularly robust strategy for avoiding certain adverse consequences of climate change. For example, although a 550 ppmv stabilisation level has been recommended as a target for international mitigation efforts, should the climate prove highly sensitive to GHGs, such a stabilisation level may be insufficient protection against certain impacts. Because the "right" target cannot be known with certainty, it is better to envision mitigation strategies as a process of sequential decision-making rather than a single event. Given such a framework, the most cost-effective option is to hedge against uncertainty, selecting a mitigation strategy that achieves present goals while preserving future options.

A number of institution have expressed this hedging strategy as the "guard rails", "tolerable windows", or "safe-landings" approaches.[37,38,39] The common element of these strategies is that some determination is made of the acceptable damages or losses from climate (i.e., a magnitude or rate of warming) as well as society's willingness to pay to mitigate GHG emissions (i.e., a rate of mitigation). The area between these two curves represents the range of allowable emissions. The fact that a specific prior emissions path is not specified allows flexibility in setting interim targets and burden-sharing, provided the window for acceptable emissions is not exceeded. However, work by the WBGU (1997) demonstrates that delays in achieving emissions reductions constrain subsequent decision-making.[40] The closer one gets to the "guard rails" or to the boundaries of the "tolerable window," the more allowable emissions become prescribed. Therefore, early action to reduce emissions provides greater flexibility at subsequent stages and also enables adjustments to the windows as more information is gained regarding the sensitivity of the climate system or the risk of unacceptable climate impacts.

4. EMISSIONS REDUCTIONS AND CLIMATE STABILISATION

As is clear from Section 3, achieving GHG stabilisation at a level consistent with the CO_2 concentration and temperature thresholds identified in Table 1 for DAI necessitates major reductions in global GHG emissions...

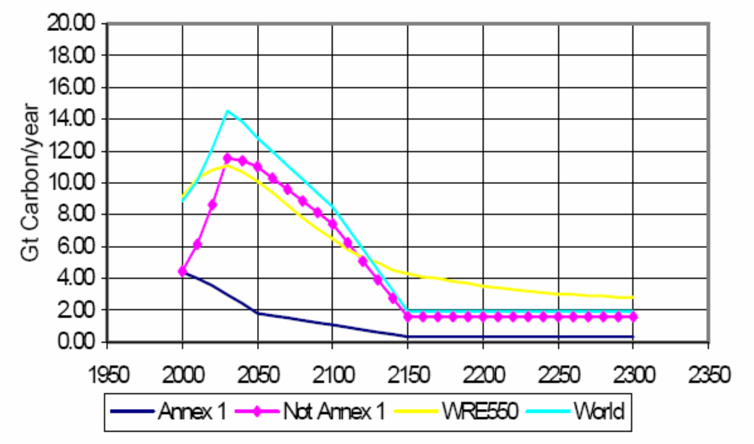

Figure 7. *RCEP pathways for 550 stabilisation. Global emissions initially exceed the WRE550 scenario before rapidly declining post-2025. World emissions are divided among Annex I nations which reduce emissions immediately and non-Annex I countries which do not undertake reductions until post-2025.*

Greenhouse gas emissions are a useful benchmark for measuring Australia's efforts in addressing the climate change challenge. While a number of institutions have advocated global GHG stabilisation levels (**Table 1**), no one country can achieve such a target through individual action. However, Australia can take measures to achieve reductions in national emissions, and in so doing, contribute to other international efforts to curb GHG emissions and, subsequently, GHG stabilisation. Although neither the international scientific nor policy communities have come to an agreement regarding what an appropriate GHG stabilisation level should be, significant emissions reductions over the next several decades would also preserve future options in the choice of a stabilisation level. Should the climate prove insensitive to anthropogenic GHG emissions, future commitments to mitigation can be made less stringent. Yet, more conservative thresholds would remain feasible should the more pessimistic projections of climate change and its impacts prevail.

Although the pursuit of emissions reductions of 60% or more cannot be translated directly into a specific stabilisation target, this emissions target does have its origins in the analysis of different stabilisation pathways, particularly the 550 ppmv stabilisation target which, as evidenced by **Table 1**, is roughly the upper limit for atmospheric GHG concentrations that avoid DAI. For example, the United Kingdom's Royal Commission on Environmental Pollution (RCEP) recommended that by 2050, Annex I emissions reductions would have to be 60% below 1990 levels in order to be on track to achieve a global 550 ppmv stabilisation target.[23] The RCEP scenario is actually more stringent post-2100 than the WRE550 scenario, under the argument that emissions are rapidly rising above those assumed in the WRE550 scenario (**Figure 7**). This general approach has been accepted by the UK's Department of Energy, which is moving forward with implementation.[41]

Sweden's updated climate change strategy has a near-term goal of meeting its Kyoto Protocol target of 2% below 1990 levels by 2008–2012, and maintaining emissions at 1990 levels over the interim period. In addition, it sets a longer term goal of reducing emissions 50% by 2050 (with per capita emissions below 4.5 tonnes/year), with further reductions beyond this point.[19]

Although the United States has opted out of the pursuit of a specific emissions target, an analysis conducted in conjunction with the U.S. Department of Energy indicated that U.S. emissions would have to be reduced by 64% below 2001 levels by 2050 if the U.S. were to meet its contribution to a 550 ppmv stabilisation target (**Figure 8**).[42] Emissions reduction targets similar to those described above have been recently adopted elsewhere. The European Union's Environment Council recommended emissions reductions by developed countries of 15–30% by 2020 and 60–80% by 2050,[43] although these are non-binding targets and have yet to be incorporated into official EU GHG reduction strategies. In Australia, the New South Wales Greenhouse Gas Office has followed the lead of the UK, with its Greenhouse Advisory Panel also recommending 60% reductions in emissions by 2050.[44]

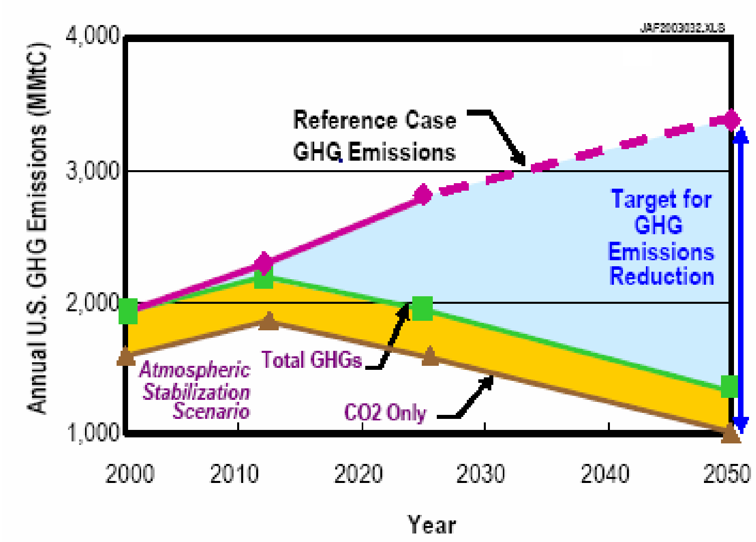

Figure 8. *Analysis of U.S. emissions pathway given a 550 ppmv stabilisation level. U.S. emissions peak in 2012, after which they decline to 64% below 2000 levels by 2050.*

Despite the precedence for the use of 550 ppmv as benchmark for estimating GHG emission reductions necessary to avoid DAI, it is clear from the range of proposed thresholds in **Table 1** that even this threshold is considered too high by some experts. Carbon dioxide and CO_2e concentration thresholds well below 550 ppmv frequently have been recommended. Furthermore, the average temperature threshold in **Table 1** is 1.5°C. **Table 2** indicates that a 550 ppmv stabilisation level is almost certain to exceed this threshold by 2100, and even a 450 ppmv stabilisation level would exceed this threshold by 2300 (see also **Figure 6**). An analysis for the International Climate Change Policy Project by the Dutch National Institute of Public Health and the Environment evaluated a range of different strategies for achieving a global CO_2

stabilisation target of 450 ppmv, found that global emissions would have to be reduced by 30–35% below 1990 levels by 2050, while Oceania's emissions would have to be reduced by 75–80% (**Figure 9**). Therefore, the goal of Annex I emissions reductions of 60% by 2050 may be considered a minimum estimate of the effort needed to achieve stabilisation to avoid DAI. Further reductions in emissions would be necessary beyond 2050, as reflected in the RCEP strategy.[23] In addition, to the extent that reductions greater than 60% by the mid-21st century are feasible, this would create the opportunity for stabilisation at levels below 550 ppmv.

What is also apparent from **Figure 9** is the disparity in emission reductions associated with developed countries such as Australia and those of the world at large. This reflects the complex issue of burden-sharing between the developing and developed worth with respect to emissions reductions. Historically, the developed world, particularly the United States and Europe, have been responsible for the majority of GHG emissions.[45] These regions also have relatively high rates of per capita energy consumption associated with mature market economies. The developing world has less historical responsibility for emissions, lower rates of energy consumption, and generally less mature economies. Thus, it is generally assumed that the developed world will take the lead in achieving GHG emissions reductions, with significant developing country participation unlikely to occur prior to 2010. For example, both RCEP and Sweden's emissions reduction estimates are dependent on the assumption that non-Annex I countries delay emissions reductions from anywhere from 0–65 years, depending upon Annex I reductions, the rates of non-Annex I emissions growth, and natural offsets and carbon sequestration (**Table 3**).[46] This system for burden sharing is based upon the "contraction and convergence" approach, which bases emissions reduction targets upon achieving an equitable global distribution of per-capita emissions.[46]

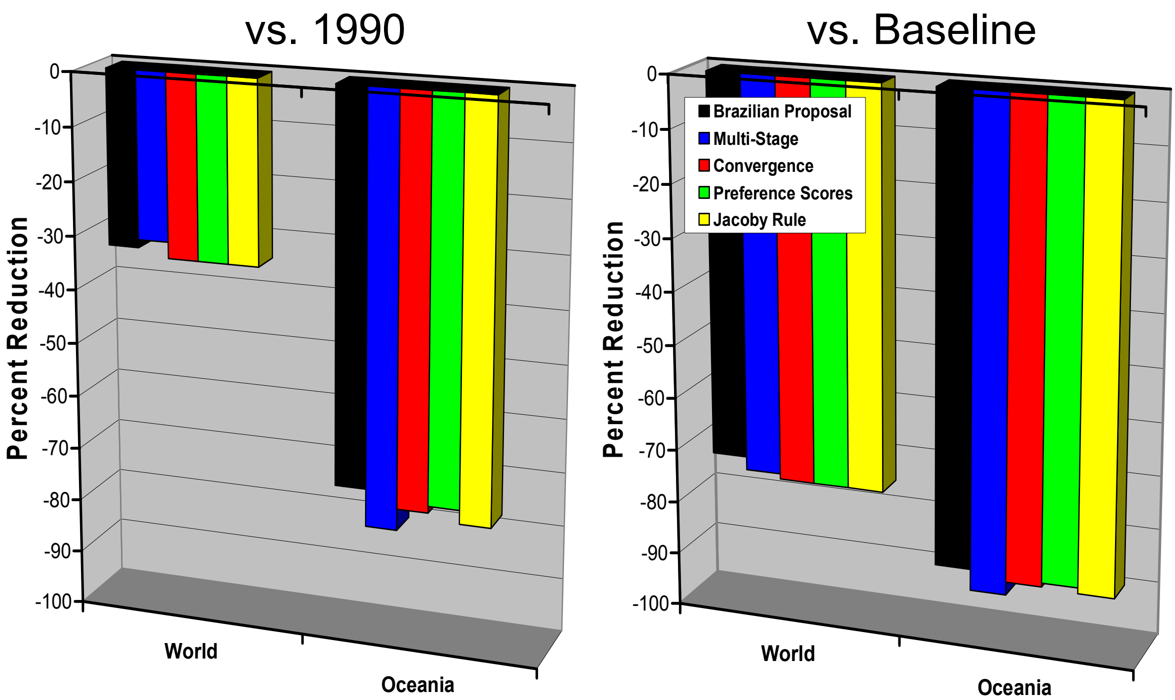

Figure 9. *Estimated emissions reductions (relative to 1990 or future baseline emissions in the absence of mitigation) necessary by 2050 to achieve a global stabilisation level of 450 ppmv CO_2. Bars represent average estimates based upon five different strategies for emissions reductions including different timing and burden sharing schemes. Estimates for Oceania are presented relative to emissions reductions for the world as a whole.*

Table 3. *Latest date by which non-Annex I countries must initiate GHG emissions reductions to achieve a 550 ppmv CO_2 stabilisation target, given different assumptions about natural carbon sequestration, emissions reductions of Annex I countries, and emissions growth rates of non-Annex I countries.*

ANNEX I CUTS BY 2050 RELATIVE TO 2000	HIGH GROWTH EMISSIONS FOR NON- ANNEX I	LOW GROWTH EMISSIONS FOR NON- ANNEX I
40%		
High natural carbon uptake	2030	2100
Low natural carbon uptake	2000 – 2010	2010 – 2060
60%		
High natural carbon uptake	2030	2100
Low natural carbon uptake	2010 – 2020	2040 – 2060
80%		
High natural carbon uptake	2030	2100
Low natural carbon uptake	2020 – 2030	2040 – 2070

As prescribed by the Kyoto Protocol, Annex I countries may indeed be willing to take the lead in pursuing reductions, but it is arguable how long Annex I countries would be willing to carry the burden alone. Rapid growth in the economies, and subsequently the GHG emissions, of the developing world means that it will soon overtake the developed world in emissions. Therefore, although GHG stabilisation can be achieved without immediate action from the developing world, at some point, it must become an active partner in international mitigation activities. Furthermore, to the extent that non-Annex I countries accelerate the initiation of emissions reductions, the lesser the burden on Annex I countries.

5. CLIMATE CHANGE AND AUSTRALIAN IMPACTS

Over the next century and beyond, climate change will result in a broad range of consequences for most regions, including Australia.[3] Although climate change impact assessment has been an active area of research for over two decades, this research has intensified in recent years as a result of growing evidence of a human influence on the climate system, direct observations of climate impacts, and increasing concern about the nature of future impacts. Some of these impacts will be large, others small, and some surprises will likely occur.

Due to uncertainties in the climate system and in systems' response to that climate, one cannot offer specific predictions regarding impacts, their rate of occurrence, and their magnitude. Instead, impacts are estimated based upon different "if. . . then" scenarios of future changes in temperature and precipitation and how systems may subsequently respond. However, when multiple scenarios are used, it is possible to gain insight into the dynamical response of systems to changes in temperature, precipitation, and sea-level and constrain the range of potential responses that are likely to occur. Such methods can often be used to quantify the likelihood of impacts and which outcomes prove to be robust in the face of uncertainty. In addition, the emergence of risk management as a tool for assessing the likelihood of specific consequences, measured by using concepts such as the coping range of climate and critical thresholds, and through integrating climate risks with other elements of change, has assisted in developing our understanding of how climate change may affect us in the future.[47]

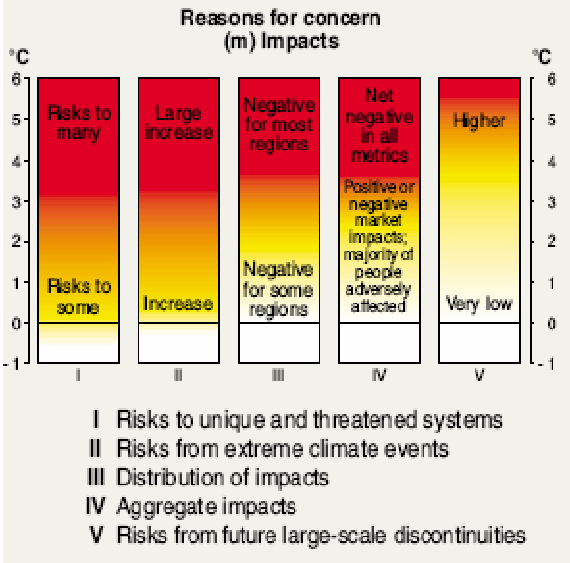

Figure 10. *IPCC's (2001) "reasons for concern," reflecting the differential vulnerability among systems to climate change and the tendency for impacts to increase with temperature.*

In assessing the impacts of climate change, one can refer to a system's *vulnerability*, meaning a system's ability to experience adverse consequences from climate change.[48] For example, the range of climate conditions that different systems can cope with before experiencing adverse effects varies significantly. Coral reef ecosystems are already experiencing adverse affects due to historical warming.[49] In contrast, economic studies of Australian and U.S. agriculture suggest economic benefits may occur for warming as high as 3–5°C, given sufficient rainfall.[50,51] A major factor affecting a system's vulnerability is the availability of mechanisms to manage or adjust to change, also referred to as *adaptive capacity*. Recent studies have indicated that corals possess adaptive responses that may enable them to expand their coping range over time, reducing their vulnerability to future temperature anomalies.[52,53] In addition, estimates of climate change impacts to U.S. agriculture vary depending upon assumptions about the uptake of adaptive responses and foresight about future climate conditions.[50] Limited adaptive capacity among populations or nations with financial, education, and technological constraints largely account for the regional variability in vulnerability to current climate conditions, as well as future climate change.

Regardless of a system's vulnerability, impacts will increase with increases in the magnitude or rate of climate change.[54] As suggested by **Figure 10**, the vulnerability of systems to climate change has largely been expressed relative to average global temperature. Yet, other climatic variables are often more important. Impacts to water resources, for example, clearly depend upon precipitation changes. Similarly, in the coastal zone, sea-level rise and storm surge may be more critical drivers than either temperature or precipitation. In some situations, climate variables may be highly interactive, meaning the magnitude of change in one variable affects the response of the system to the other. For example, the impacts associated with a large temperature increases may be quite high if precipitation declines, but more modest if precipitation keeps pace with temperature. Thus in communicating the risks of climate change, it is important to acknowledge these complex interactions.

This section summarizes a range of climate change impacts, divided into five core sectors: natural ecosystems; crop agriculture, forestry, and livestock; water resources; public health; and human settlements and infrastructure. The general factors that affect the vulnerability of these sectors are discussed. This is followed by a summary of results from impact assessments specific to Australia, presented as a gradient over a range of 21st century temperature changes from ~1°C up to ~5+°C (roughly the upper estimate for projected 21st century global mean temperature change). These impacts are integrated into a series of simple figures illustrating the relative vulnerability of these systems to the combined effects of changes in temperature and precipitation conditions. In addition, two cross-cutting issues relevant to understanding climate change are discussed further: the potential for climate extremes and large-scale singularities. The impacts associated with different magnitudes of temperature change can be compared with estimated temperature change in the absence of mitigation or with different mitigation targets and/or GHG stabilisation levels (Section 3), to gain greater insight regarding the benefits of GHG mitigation and stabilisation for avoiding impacts (Section 6).

5.1 Natural Ecosystems

The world's natural ecosystems are considered vulnerable to climate change because of human dominance of ecological processes at the global scale. Patterns of temperature and precipitation are key factors affecting the distribution and abundance of species, and describe the climatic envelope of each species or community. The climatic envelope in which the majority of a population of a species is found is termed core habitat; impact modelling of climate change assesses how climatically-defined core habitat may change. How this translates into risk to species and populations is unknown, therefore ecological assessment requires that a precautionary approach be taken to prevent irreversible consequences.

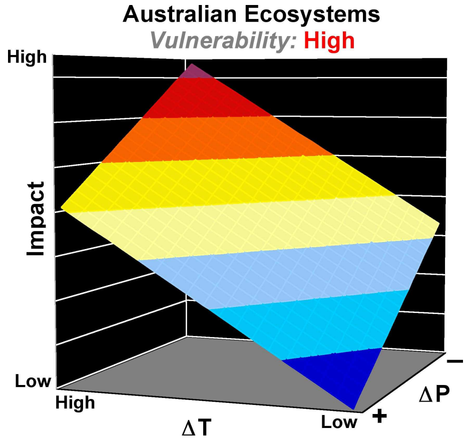

Figure 11. *Illustration of the vulnerability of Australia's ecosystems to changes in temperature and precipitation.*

Projected changes in climate will have diverse ecological implications.[55] Habitat for some species will expand, contract, and/or shift with the changing climate, resulting in habitat losses or gains, which could prove challenging, particularly for species that are already threatened or endangered. Species within ecosystems have an inherent capacity (behavioural, physiological, and genetic) to cope with some degree of climate variability, provided variability is maintained within a certain range. Yet this coping range can be relatively narrow for many species, and may be exceeded by short-term changes in climate extremes or long-term changes in average climate conditions. Recent studies indicate that globally, natural ecosystems are already responding to climate change.[56] For some species, these responses appear to part of coping strategies, for others adverse effects including localized population extinctions have been observed.[57] Both increases in atmospheric CO_2 influencing vegetation responses and animal-plant interactions, and invasive species dynamics will also change under climate change, but the nature of such changes remains unclear.

Table 4. *Projected Impacts to Australian Ecosystems*	
ΔT (°C)	**Projected Impact**
<1	10–40% shrinkage of snow-covered area in the Australian Alps[58]
	18–60% decline in 60-day snow cover in the Australian Alps[58]
	Bleaching and damage to the Great Barrier Reef equivalent to 1998 and 2002 in up to 50% of years[59,60]
	60% of the Great Barrier Reef is regularly bleached[61]
	Habitat is lost for 14% of Victoria's marine invertebrates[62]
	50% decrease in habitat for vertebrates in northern Australia tropics[63 ,64]
	<5% loss of core habitat for Victorian and montane tropical vertebrate species[65]
	28% of Dryandra species' core habitat is significantly reduced in SW Australia[66]
	4% of Acacia species' core habitat is significantly reduced in SW Australia[66]
	63% decrease in Golden Bowerbird habitat in N Australia[67]
	Habitat for 3 frog and 15 threatened/endangered mammals in W Australia is lost or restricted[66]
	50% decrease in montane tropical rainforest area in N Australia[68]
1–2	Up to 58–81% of the Great Barrier Reef is bleached every year[61]
	Hard coral reef communities are widely replaced by algal communities[69]
	90% decrease in core habitat for vertebrates in northern Australia tropics[63,64]
	5–10% loss of core habitat for Victorian and montane tropical vertebrate species[65]
	88% of butterfly species' core habitat decreases[70]
	66% of core habitat for Dryandra species is significantly reduced in SW Australia[66]
	100% of Acacia species are eliminated in SW Australia[66]
2–3	97% of the Great Barrier Reef is bleached every year[61]
	10–40% loss of core habitat for Victoria and montane tropical vertebrate species[65]
	92% of butterfly species' core habitat decreases[70]
	98% decrease in Bowerbird habitat in N Australia[67]
	80% loss of freshwater wetlands in Kakadu (30 cm sea level rise)[71]
3–4	Catastrophic mortality of coral species annually[61]
	95% decrease in distribution of Great Barrier Reef species[61]
	65% loss of Great Barrier Reef species in the Cairns region[59]
	20–85% shrinkage of total snow-covered area in the Australian Alps[58]
	38–96% decline in 60-day snow cover in the Australian Alps[58]
	30–70% loss of core habitat for Victoria and montane tropical vertebrate species[65]
4–5	60–90% loss of core habitat for Victoria and montane tropical vertebrate species[65]
>5	90–100% of core habitat lost for most Australian vertebrates[63,64]

A number of Australia's ecosystems are vulnerable to changes in temperature and precipitation (**Figure 11**),[3] and thus significant adverse consequences from climate change are projected, even for relatively small shifts in climate conditions. The Great Barrier Reef, a UNESCO World Heritage area, is particularly vulnerable to climate change, given the narrow coping range and limited adaptive capacity of corals. Historically unprecedented rates of bleaching have occurred over the past two decades and considerable losses or contractions of species associated with coral communities are projected for a further warming of only 1°C (**Table 4**). Similarly, high altitude montane ecosystems are sensitive to climate change-induced reductions in winter snow cover, and the highland rainforests of northern Australia are projected to decrease by 50% for just a 1°C increase in temperature. Given higher magnitudes of warming, adverse effects for certain groups of species are expected to become progressively worse.

Annual damage to the Great Barrier Reef increases to the point of catastrophic failure, snow cover and duration decreases substantially, and species are lost from vertebrate and invertebrate communities in northern and southeast Australia.

5.2 Cropping, Forestry, and Livestock

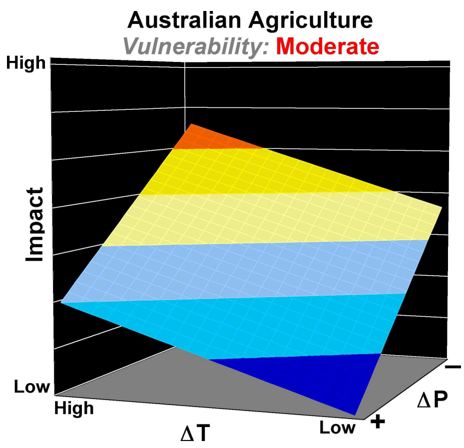

Figure 12. *Illustration of the vulnerability of Australia's agriculture to changes in temperature and precipitation.*

The cropping, forestry, and livestock sectors are influenced by changes in climatic conditions and also by increases in atmospheric CO_2. The productivity of crop agriculture and forestry is dependent upon temperatures, the length of the growing season, available soil moisture, atmospheric CO_2 and climate extremes such as droughts and storms. Livestock are sensitive to temperature, water availability and access to food. Intensive management of these sectors can reduce their vulnerability to climate relative to extensive production ecosystems, but failure can be much more expensive if critical thresholds are exceeded in such systems. Over time, people have expanded the coping range of agriculture and livestock by breeding strains more tolerate of a wider range of climate conditions. In addition, agricultural practices such as irrigation and pest control further expand the resilience of these sectors to climate conditions. Nevertheless, climate extremes are still capable of inflicting substantial damages on agriculture, forestry, and livestock. For example, prolonged droughts reduce agricultural productivity, while wildfires in arid can affect valuable forest land.

Climate change will probably posed mixed consequences for Australian agriculture, forestry, and livestock, depending upon interactions between temperature, precipitation and the response of vegetation to the "CO_2 fertilization" effect (**Figure 12**). Given sufficient increases in precipitation, wheat yields are projected to increase for warming of up to at least 3–4°C (**Table 5**). Under less favourable precipitation scenarios, however, such increases in productivity may not be realized, and, large reductions in precipitation and increases in drought could severely impact agriculture. In addition, despite domestic increases in wheat productivity, exports are projected to decline. Agricultural pests, such as the Queensland fruit fly and the light brown apple moth are also projected to increase, which will affect net changes in economic welfare.

For the vast bulk of Australia's plantation forests the interaction between temperature and water availability is the key issue, with productivity being predominantly water limited, and "growing season" often being more influenced by water availability. For up to 1°C – increased precipitation results in increased yield, while decreased precipitation results in decreased yields (Table 4). Impacts to the timber industry also vary with the type of timber and geographic location. For example, warming of just 1°C has been projected to exceed the core habitat of 25% of Eucalyptus species. However, knowledge of productive growth of a forest species beyond its core climatic envelope can provide valuable information on how species may acclimatise to changes.[72] For higher magnitudes of warming, forestry in N Australia suffers lowered productivity, while in the cooler, less water limited areas of S Australia forest productivity increases.[75]

Average changes will be far less important in this context than more extreme events, which can have catastrophic impact on the economic viability of long-rotation crops. Large areas of Australian plantations are "on the edge" in terms of drought risk. Fire frequency and severity is a major risk for plantations. A number of key plantation pests are favoured by warm summer conditions or tree drought stress.

Temperature increases will stress livestock, leading to reductions in milk production even for warming of just 1°C (**Table 5**). Decreases in precipitation will lower the quality of native pasture land, resulting in reduced productivity of native pasture land for grazing livestock. Meanwhile, like crop agriculture, pests such as ticks may reduce cattle productivity.

Table 5. *Projected impacts to Australian Agriculture, Forestry, Livestock*

ΔT (°C)	Projected Impact
<1	$4.4 million/year to manage with southward spread of Queensland fruit fly[73]
	$1.1 million/year benefit with contraction in range of Light brown apple moth[74]
	Increase in "generic" timber yields (under wet scenarios) [75]
	Decrease in "generic" timber yields (under dry scenarios)[75]
	25% of core habitat lost for Eucalyptus[76]
	250–310 litre annual decline in milk production per cow in Hunter Valley[77]
	8% reduction in native pasture growth (for 11% decrease in precipitation)[78]
	13% reduction in livestock carrying capacity in native pasture systems (for 11% decrease in precipitation)[78]
1–2	12% chance of decreased wheat production (without adaptation) [79]
	32% chance of wheat crop value below current level (without adaptation)[79]
	91% chance of wheat exports being below current level (without adaptation) [79]
	$12.4 million/year to manage with southward spread of Queensland fruit fly[73]
	$5.7 million/year benefit due to reduction of Light brown apple moth[74]
	40% of core habitat lost for Eucalyptus[76]
	38% increase in tick-related losses in net cattle production weight [80]
2–3	31% reduction in native pasture growth (for 32% precipitation decrease)[78]
	40% reduction in livestock carrying capacity of native pasture systems (for 32% precipitation decrease) [78]
3–4	32% chance of decreased wheat production (without adaptation)[79]
	45% chance of wheat crop value being below current level (without adaptation)[79]
	55% of core habitat lost for Eucalyptus[76]
	25–50% increase in "generic" timber yield in cool and wet parts of S Australia[75]
	25–50% decrease in "generic" timber yield in N Queensland and Top End[75]
	6% decline in Australian net primary production (for 20% precipitation decrease) [75]
	128% increase in tick-related losses in net cattle production weight [80]

5.3 Water Resources

Water resources are increasingly a core issue for both the developed and, particularly the developing world due limited resources and a growing global population. Furthermore, water resources supply a broad range of goods and services, including drinking water, waste management, hydroelectric generation, irrigation, recreation and tourism opportunities, and habitat for wildlife. Both past and present challenges to water management have demonstrated the powerful influence of climate variability and change. A particular challenge for water resources management are extreme events, such as prolonged droughts which reduce water availability, or periodic extreme rainfall events, which result in extensive run-off and increase the risk of flooding.

Australia is currently facing extensive water resource challenges, particularly in the southwest, where current precipitation, run-off, and stream flows have dropped to levels well below long-term average (**Figure 13**). Water storage in reservoirs is also well below capacity throughout much of West and South Australia, Victoria, and Queensland. The current pressures placed on Australian water resources are indicative of their general high vulnerability to climatic change (**Figure 14**). Many of Australia's most important catchments are covered by native forest. The impact of climate change on growth, species composition, and frequent/severity of fire and pest incursion may profoundly impact on water supply from these catchments, including the prospect of water losses due to further reafforestation in cleared catchments.[81] Climate change will also influence water demand for irrigation and other uses. If climate change increases demand and decreases water supply, then there is a need to supplement supply or reduce demand. Water quality is likely to decrease under climate change, as there will be less water for dilution of saline base flows. This has the will require the application of more water to provide the leaching fraction in some irrigation areas.

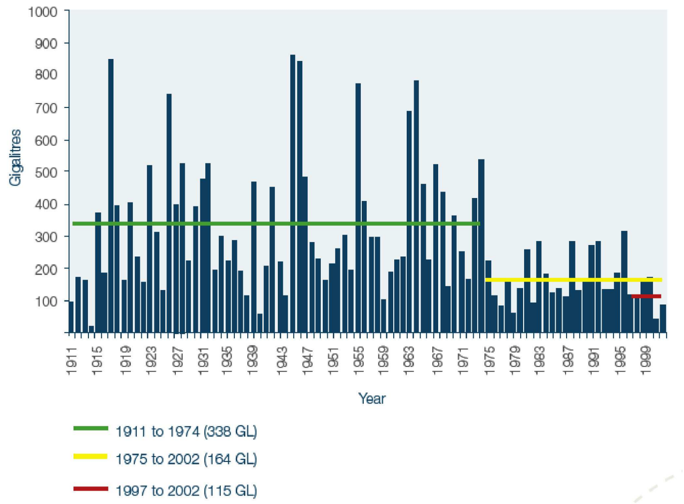

Figure 13. *Long-term annual average streamflows for major surface water sources for the Perth water supply system.*

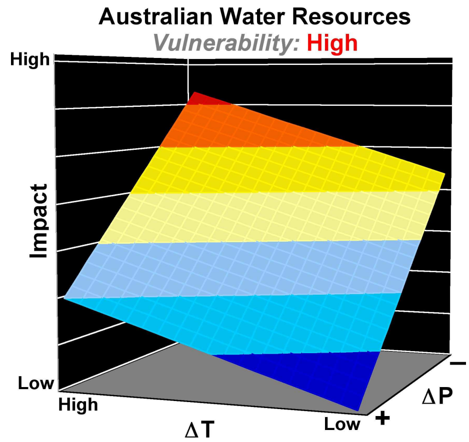

Figure 14. *Graphic illustration of the vulnerability of Australia's water resources to changes in temperature and precipitation.*

Inflows to reservoirs in NSW have been projected to decrease by up to 15% for just a 1°C increase in temperature (**Table 6**). Generally, such decreases grow in magnitude with higher magnitudes of warming as demonstrated by impact assessments for a range of reservoirs across NSW, Victoria, and South Australia (Table 11). In addition, these decreases have important ecological implications as well, by affecting wetlands important for bird breeding as well as other wildlife. These projected impacts are highly dependent upon changes in rainfall regimes. However, CSIRO projections generally indicate rainfall, particularly in winter, will decrease substantially in Victoria, S Australia, and W Australia over the 21st century. Changes are more uncertain for other regions.

Table 6. *Projected impacts to Australian Water Resources*

ΔT (°C)	Projected Impact
<1	0–15% likely decrease in flow to Burrendong Dam and Macquarie Marshes in Macquarie River Basin (NSW)[82,83]
	3–11% decrease in Melbourne's water supply[84]
1–2	12–25% decrease in flow in the Murray Darling Basin[85]
	7–35% decrease in Melbourne's water supply[84]
2–3	5–35% likely decrease in flow to Burrendong Dam and Macquarie Marshes in Macquarie River Basin (NSW)[82,83]
3–4	50% chance threshold for bird breeding exceeded in Macquarie Marshes[82,83]
	16–48% decrease in flow in the Murray Darling Basin[85]

5.4 Public Health

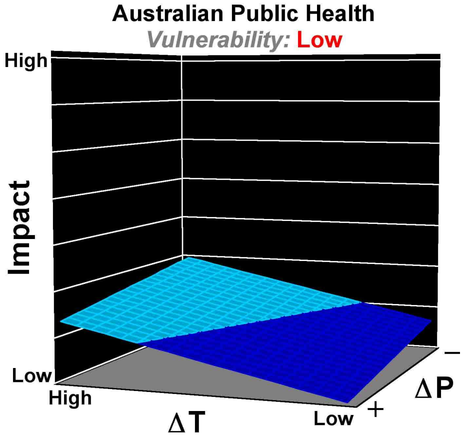

Figure 15. *Illustration of the vulnerability of Australia's public health to changes in temperature and precipitation.*

Assessing the implications of climate change for public health remains quite challenging due to the existence of complex interactions among climate, the environment, and socioeconomic factors. The direct effects of climate change include the potential for increases in temperature to increase heat-related, and reduce cold-related, illness and death.[54] The former largely occurs in extreme heat events, such as that associated with the 2003 mass casualty event in Europe.[86] Increases in winter temperatures may reduce illness and mortality, but it is unclear the extent to which seasonal patterns of infectious disease are in fact temperature dependent, and thus how much higher temperatures may alleviate cold-weather illness and mortality.[87] Other extreme weather events such as severe storms, wind, and flooding also contribute to injury and mortality on an annual basis.

In addition to the direct health effects of climate, there are a range of indirect consequences. Higher temperatures have been linked with higher levels of tropospheric ozone, particularly in urban areas, which can induce respiratory and cardiovascular illness and death.[54] The risk of vector borne disease is influenced by climate, due to the effects of temperature and precipitation on disease vectors in the environment (e.g., mosquitoes, ticks).[54] Temperature and precipitation extremes have also been associated with increases in food and water-borne illness.[54]

Due to its relatively high adaptive capacity, the vulnerability of Australia's public health sector is relatively low (**Figure 15**), although one can identify demographic groups, such as Australia's aboriginal population, with elevated vulnerability to health challenges due to limited access to financial and public health resources. The effects of climate change on heat-related mortality suggest that increases in temperature combined with population growth may result in an increase in heat-related deaths over the next century after adjusting for decreases in cold- and ozone-related mortality (**Table 7**). Climate change could cause large increases in flooding deaths and injuries, depending upon future changes in precipitation extremes. Climate change could cause the range of mosquito vectors for dengue and malaria to expand southward. However, public health interventions targeting malaria during the 1960s have largely eliminated the risk of transmission and reintroduction of the disease is unlikely. In contrast, the transmission of dengue continues in Australia, although cases are largely confined to northern Queensland. Proper public health interventions may prevent substantive increases in dengue transmission. Some studies have also suggested that climate change could increase transmission of Ross River virus in regions of Australia, but less is known about the epidemiology of this disease. Climate change could increase the risk of food and water-borne illnesses, yet again these can be addressed through appropriate infrastructure management and food handling.

Table 7. *Projected Impacts to Australian Public Health*

ΔT (°C)	Projected Impact
<1	1,185–1,385 more deaths in 65-year age group in temperate Australian cities[88]
	4–12 more deaths in 65-year age group in N tropical cities[88]
	No increase in population at risk of dengue[88]
1–2	Southward spread of malaria receptive zones[88]
	Population at risk of dengue increases from 0.17 million to 0.75-1.6 million[88]
	10% increase in diarrhoeal diseases among Aboriginal children in central Australia[88]
	100% increase in number of people exposed to flooding in Australia and New Zealand[88]
	Increased influx of refugees from Pacific Islands[88]
2–3	Further southward spread of malaria receptive zones[88]
	Temperature related mortality among people 65+ years in Australian capital cities increases by 89–123%[89]
	Southward expansion of dengue transmission zone as far as Brisbane[89]
3-4	Temperature related mortality among people 65+ years in Australian capital cities increases by 144–200%[89]
	Southward expansion of dengue transmission zone as far as Sydney[89]

5.5 Settlements and Infrastructure

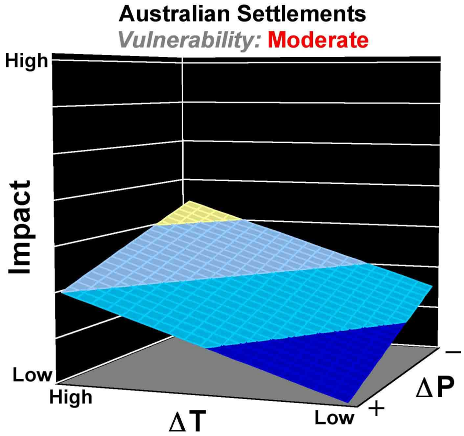

Figure 16. *Illustration of the vulnerability of Australia's public health to changes in temperature and precipitation.*

Many aspects of human settlements where people live, work, and play are exposed to the climate, prompting concern about the potential impacts of climate change. Those aspects of human settlements that have received the most focus include energy, the built environment of the coastal zone, transportation, and recreation/tourism. Human settlements, particularly those in developed countries, tend to have a fairly broad coping capacity and are generally resilient to daily and seasonal variability in the climate system. Thus, a particular concern for settlements is the potential for changes in the frequency of climate extremes (see below) – more frequent heat waves, more frequent or intense storm events, more frequent floods. All of these would pose significant challenges to human settlements that would ultimately necessitate adaptive responses, although their implications for communities have in many cases not yet been quantified.

Australia's settlements are moderately vulnerable to climate change (**Figure 16**), largely due to the potential impacts posed by extremes of temperature and precipitation. Australia's energy sector may be one of the first components of Australian settlements to respond to climate changes. Impact assessments indicate that just a 1°C increase in average temperatures would be sufficient to increase peak demand in Adelaide and Brisbane, and reduce transmission efficiency (**Table 8**). Yet, these increases may be offset by initial decreases in electricity demand in Melbourne and Sydney and reduced demand for natural gas in Melbourne. For higher levels of warming, electricity demand in Brisbane, Melbourne, and Adelaide increases, while demand in Sydney remains at slightly lower levels than present. Temperature increases of 2-3°C are projected to increase maintenance costs for transportation infrastructure.

Australia's coastal zone is of particular concern, due to its thousands of kilometres of coastline and the concentration of much of Australia's population, commerce, and industry in the coastal zone. Climate modelling has suggested that storm winds, including those associated with tropical cyclones, may become more intense with a warming of 1–2°C (**Table 8**). This combined with sea-level rise would result in higher storm surge during storm events and a greater area flooded. In addition, higher wind speeds would increase storm damages as they tend to increase with the square of wind speed.[90] Sea-level rise and storm events also contribute to coastal inundation and beach erosion, which may affect popular tourism and recreation areas. At higher levels of warming, coastal impacts become more severe with higher storm winds and sea levels.

Table 8. *Projected impacts to Australian Settlements*

ΔT (°C)	Projected Impact
<1	3% decreases in thermal efficiency of electricity transmission infrastructure[91]
	Decrease in demand for natural gas for heating in Melbourne[92]
	Peak electricity demand in Melbourne and Sydney decreases up to 1%[93]
	Peak electricity demand in Adelaide and Brisbane increases 2–5%[93]
1–2	100 year storm surge height around Cairns increases 22%; area flooded doubles[94]
	Peak electricity demand in Melbourne and Sydney decreases 1%[93]
	Peak electricity demand in Adelaide and Brisbane increases 4–10%[93]
2–3	17% increase in road maintenance costs over most of Australia[95]
	Decreases in road maintenance costs in S Australia[95]
	Peak electricity demand in Adelaide, Brisbane and Melbourne increases 3–15%[93]
	Peak electricity demand in Sydney decreases 1%[93]
3–4	Oceania experiences net loss of GDP[96]
	Peak electricity demand in Adelaide, Brisbane and Melbourne increases 5–20%[93]
	Peak electricity demand in Sydney decreases 1%[93]
4–5	Peak electricity demand in Adelaide, Brisbane and Melbourne increases 9–25%[93]
	Peak electricity demand in Sydney decreases 0.5%[93]
>5	Peak electricity demand in Sydney decreases 0%[93]
	Peak electricity demand in Adelaide, Brisbane and Melbourne increases 10–25%[93]

5.6 Extreme Weather Events

A key cross-cutting issue that emerges from examining climate change impacts across multiple sectors is the significant influence of extreme weather events on the consequences of climate change. For example, in the preceding discussion of sectoral impacts, the potential for extremes were identified as an important factor affecting the occurrence of impacts. Extreme events tend to inflict large environmental and economic costs, which is exacerbated by the fact that they can be difficult to adequately manage through adaptive processes. Globally, the World Meteorological Organization has claimed that extreme events are on the rise as a result of anthropogenic perturbation of the climate system,[97] and climate models indicate the potential for increases in extremes of temperature, precipitation, droughts, storms, and floods.[54]

Table 9. *Climate Change and Extreme Weather Events*	
ΔT (°C)	**Projected Impact**
<1	70% increase in droughts in New South Wales[98]
	10–20% increase in the intensity of extreme daily rainfall in New South Wales[98]
	18% increase in annual days above 35°C in South Australia[99]
	25% increase in annual days above 35°C in Northern Territory[100]
	6% decrease in extreme daily rainfall in Victoria[101]
1-2	100 year storm surge height around Cairns increases 22%; area flooded doubles[102]
	25% increase in 100-year storm tides along eastern Victoria coast[103]
2–3	5–10% increase in tropical cyclone wind speeds[102]
	20–30% increase in tropical cyclone rainfall[102]
	12–16% increase in 100-year storm tides along eastern Victoria's coast[103]
	10% increase in forest fire danger index in N, SW, and W Australia[104,105]
	More than 10% increase in forest fire danger index in S, central, and NE Australia[104,105]
>5	30% increase in 100-year storm tides along eastern Victoria coast[103]
	25% increase in extreme rainfall in Victoria[101]
	173% increase in annual days above 35°C in Northern Territory[100]
	150% increase in annual days above 35°C in South Australia[99]

Climate studies from Australia indicate that for a warming of just 1°C, both drought and extreme rainfall in NSW increase substantially (**Table 9**). Extreme rainfall increases in Victoria as do the number of days experiencing temperatures above 35°C in South Australia and the Northern Territory. For higher magnitudes of warming, cyclone wind speeds, rainfall, and storm surges become more intense (see also Settlements and Infrastructure, above), and increases in fire risk are also projected. These increases in Australian extremes must also be considered in the context of changes in Australia's socioeconomic context. Steady growth in Australia's population combined with the concentration of Australia's population within 50 km of the coast has exposed greater numbers of people, wealth and infrastructure to extreme weather events. These socioeconomic trends are projected to continue for at least the next half century, and thus Australia's vulnerability to extreme events will continue to increase.

5.7 Large-Scale Singularities

Large-scale singularities, complex non-linear responses where systems switch from one state to another, could cause a broad range of direct and indirect consequences to many regions of the world, including Australia. Historical and paleological data provide ample evidence that singularities and abrupt changes in the climate system have occurred repeatedly in the past. Perhaps the singularity of most immediate relevance to Australia is the collapse (regional or even global) of coral reef ecosystems, which appear to switch quite rapidly (i.e., over a narrow temperature range) from being healthy to being stressed, bleached, or eliminated.[45] Ecosystem changes further a field may also ultimately have affects on climate change in Australia. For example, carbon cycle modelling as suggested that forest dieback in tropical regions could ultimately transform the terrestrial biosphere from a sink for carbon to a source – increasing the net concentration of CO_2 in the atmosphere.[106] Recent work in the UK indicates that climate change is causing carbon to be released from soils at a rate equivalent to almost 10% of UK annual industrial CO_2 emissions – potentially offsetting reductions in anthropogenic emissions.[107]

For a number of years, scientists have expressed concern about the potential for climate change to destabilize the large ice sheets of Greenland and West Antarctica.[108] Global warming as well as the melting of glaciers and ice sheets (which increases the flux of freshwater to the oceans), could destabilize the global ocean thermohaline circulation (THC). Such destabilisation could slow its circulation, potentially to the point of complete collapse, causing regional climate shifts with significant environmental and economic consequences.[109,110] Melting of glaciers and ice sheets also contributes to sea-level rise. Vast quantities of ice are locked away in the ice sheets of West Antarctica and Greenland, collectively equivalent to approximately 12 meters of sea-level rise. Destabilisation or collapse of these ice sheets would lead to centuries of irreversible sea-level rise and coastal inundation around the world.

Paleological data indicate that abrupt climate shifts have occurred in the past as a result of catastrophic release of GHGs, primarily methane, from methane hydrates in the ocean's sediments. There has been some investigation of the causes of this release,[111] and speculation regarding the potential for anthropogenic climate change to once again destabilize this reservoir, resulting in a large-scale release of methane.

Although such singularities are potential consequences of a changing climate, the probability of specific events and the time scales over which they would occur (or even whether they would occur at all) is quite uncertain. Yet, the consequences of such events, should they occur, would be large and global. As such, much of the interest in defining DAI under the UNFCCC's Article II has emphasized the importance of mitigating GHG emissions to ensure such singularities are avoided. However, the climate thresholds for some of these singularities may be quite low. Hansen (2005) recently suggested that the threshold for an irreversible loss of the Greenland ice sheet may be as low as 1°C (**Table 1**, **Table 10**). For 1–2°C, climate models indicate the THC begins to show signs of moderate weakening. For 2–3°C, the THC weakens further, and collapse of the Greenland or West Antarctic ice sheets become even more likely. For 3–4°C, coral reefs suffer catastrophic failure and the terrestrial biosphere becomes a net CO_2 source. By 4–5°C, the THC may be pushed to the point of collapse.

Table 10. *Projected Large-Scale Singularities from Climate Change*

ΔT (°C)	Projected Impact
<1	Threshold for dangerous climate change (e.g., Greenland ice sheet mass balance).[112]
	14% decrease in N Atlantic THC[113]
	Small risk of major change in THC[114]
2–3	Effects on THC begin to occur [115]
	Significant reduction in THC[1]
	20–25% reduction in THC[116]
	5% chance of major change in THC[114]
	Threshold for collapse of the WAIS exceeded[108]
	Threshold for irreversible melting of Greenland Ice Sheet exceeded[117]
3–4	Low risk of large-scale singularities[1]
	10–15% chance of major change in THC[114]
	Threshold for complete shutdown of THC exceeded[118,119]
	15–20% chance of major change in THC[114]
	Threshold for complete shutdown of THC exceeded[120]
	Moderate risk of large-scale singularities[1]
	Terrestrial biosphere switches from net CO_2 sink to net source[106]
>5	20–30% chance of major change in THC[114]
	High risk of large-scale singularities[1]

6. BENEFITS OF GREENHOUSE GAS MITIGATION FOR AUSTRALIA

There are obviously difficult challenges associated with quantifying the relationships between anthropogenic GHG emissions, climate response, and downstream impacts to human and natural systems. The introduction of human agency and management decisions into this equation adds another set of challenges, yet it is important to consider how societal decisions about its activities and behaviours could influence future climate and environmental outcomes. For example, what benefits may be achieved with respect to avoided climate change impacts given an emissions reduction target such as the 60% reduction in developed country emissions modelled by The Allen Consulting Group for the Australian Business Roundtable on Climate Change.

6.1 Constrained Global Warming

The initial benefit of GHG mitigation would be reductions in the upper limit for future global warming, and subsequently regional climate change. As mentioned previously, some nations view 60% reductions by 2050 as consistent with placing the world on a path to achieving a 550 ppmv CO_2 stabilisation level. According to climate model results with the WRE550 stabilisation scenario, this level of mitigation would limit 21st century global warming to 1.5–2.9°C, with an additional 0.3–0.9°C of warming in subsequent centuries. Although this range is generally warmer than the temperature thresholds provided in **Table 1**, it overlaps with most of the proposed thresholds and the midpoint of this range (2.2°C) remains below the recent median estimate for DAI from Mastrandrea and Schneider (2004).[15] Perhaps more importantly, a 550 ppmv stabilisation target would reduce the upper limit for 21st century warming (5.8°C)[1] by approximately 50%. The warming avoided at the global level would also translate into reduced warming throughout Australia (Figure 17).[121]

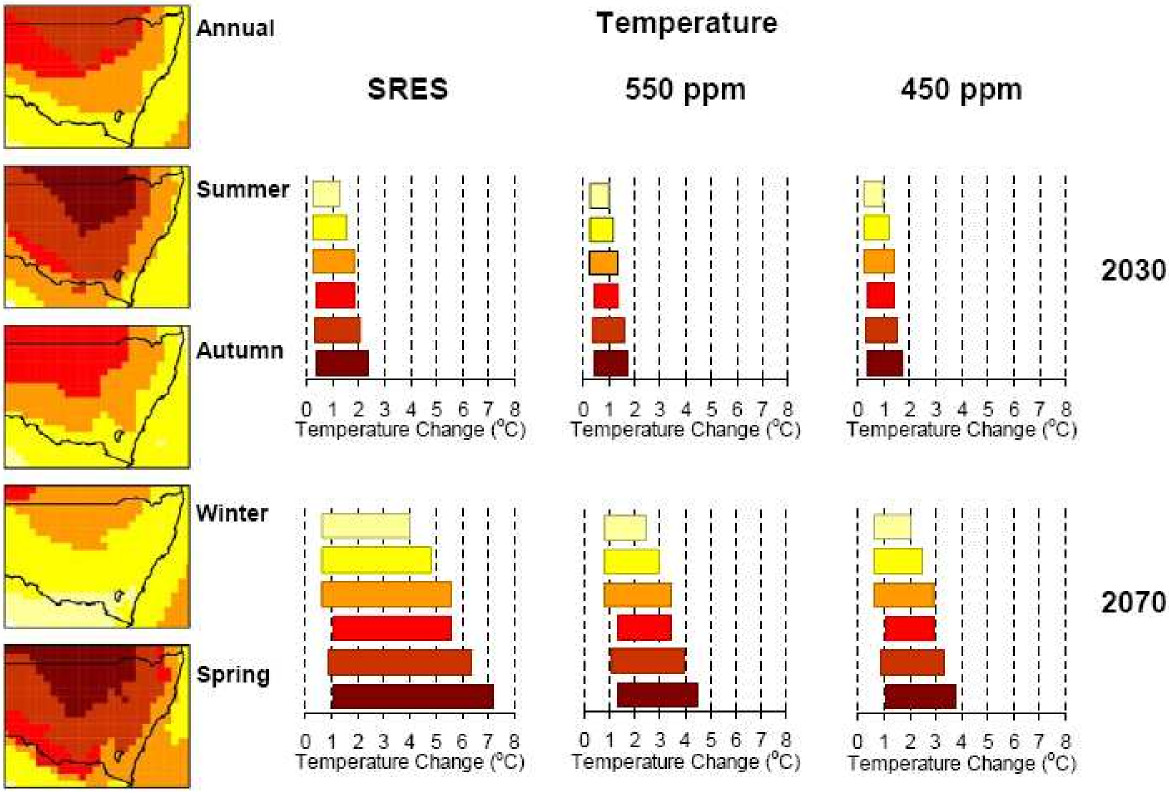

Figure 17. *Projected temperature change for New South Wales in 2030 and 2070 for the IPCC's SRES scenarios and the WRE550 and WRE450 stabilisation scenarios.*

However, it is becoming increasingly clear that 550 ppmv may not be a sufficient stabilisation goal for preventing DAI. Emission reductions beyond 60% by 2050 would leave the option for stabilising at 450 ppmv or lower open. This would limit 21st warming to approximately 1.2–2.3°C, with an additional warming of 0.3–0.6°C in subsequent centuries. Such a threshold is thereby more consistent with the temperature thresholds for DAI in **Table 1**, although additional warming beyond 2100 would exceed the mean threshold of 1.5°C. A 450 ppmv stabilisation target would reduce the upper limit for 21st century warming by approximately 70% and also achieve greater reductions in Australian climate change (**Figure 17**).

There are, however, limits to the benefits of GHG mitigation with respect to avoiding future climate change. For example, assuming stabilisation of CO_2 below current levels (e.g., 350 ppmv) were feasible, this would reduce 21st warming to approximately 1.0–2.0°C.* Though this range represents a significant avoidance of global warming from a business-as-usual scenario, because achieving stabilisation at concentrations below current atmospheric concentrations is likely an unrealistic scenario, it also represents the commitment to future climate change that humans have already placed in the pipeline.

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* Data for a 350 ppmv stabilisation level do not appear in **Table 2**, as this scenario was not considered in the IPCC Third Assessment Report. Twenty-first century temperature changes reported here for this scenario are based upon model runs with the MAGICC simple climate model.

6.2 Avoided Impacts

The avoidance of global warming achieved via GHG mitigation would have downstream benefits with respect to avoided climate change impacts. Due to the commitment to climate change, it is no longer possible to prevent all the adverse impacts of global climate change. Nevertheless, developed country emissions reductions of 60% or more by 2050 would enhance the likelihood of avoiding some of the more catastrophic consequences, while ensuring that unavoidable impacts are less severe. Undoubtedly, as both climate change and scientific research advances, knowledge regarding the consequences of climate change will grow, enabling more refined estimates of impacts and the effort required to protect valued environmental systems. Yet, generally, insight regarding the benefits of different GHG stabilisation levels can be gained by comparing the range of temperatures associated with a given stabilisation level (e.g., **Table 2**) with the range of impacts associated with different magnitudes of global warming described previously. Because mitigation generally reduces the upper limit for future temperature change, the primary benefit of mitigation is the minimization or elimination of climate change impacts associated with high magnitudes of warming. However, even systems that are adversely affected at low levels of warming would still benefit from mitigation.

For example, given that warming of just 1°C may exceed the threshold of coping capacity for the Great Barrier Reef and other coral ecosystems, it may be too late to avoid substantial impacts to these systems, even with aggressive, early mitigation action. However, mitigation may prevent the complete loss of coral reef ecosystems. Mitigation would reduce not just the magnitude, but also the rate of future climate change, which may give natural ecosystems such as coral reefs greater time to adapt. As a result, coral communities may avoid the loss of at least the more heat-tolerant species, thereby maintaining the function, goods, and services of reef ecosystems.

Early and aggressive mitigation may also help ensure that the impacts to agriculture, forestry, and livestock would be relatively moderate. Emission reductions of 60% or more by 2050 would prevent some of the worst-case scenarios for temperature and, particularly, precipitation changes in Australia. Although highly vulnerable systems such as the forests of northern Australia would still be adversely affected, crop agriculture and other forestry activities may be more likely to experience the benefits of climate change, rather than the damages. Water availability and quality for agricultural, as well as commercial and residential uses would remain a challenge, yet mitigation could assist in avoiding some of the more extreme impacts to Australia’s water resources.

Much of the public health impacts of climate change could be prevented via GHG mitigation by reducing the number of high temperature days and subsequent heat-related illness and death. Moderating changes in climate would also reduce the likelihood of significant changes in the distribution and abundance of disease vectors. Mitigation would also reduce future sea-level rise, coastal inundation, and erosion as well as other threats to built infrastructure within communities.

Due to the commitment to climate change, even with early action to reduce GHG emissions, there is likely to be an increased risk of extreme weather events, such as potentially more intense cyclones, and extremes of temperature and precipitation. Yet the frequency and intensity of such events would be dampened. In addition, the risk of large-scale singularities would be significantly reduced. Major reductions in the THC would likely be avoided, and warming would be limited to below the threshold for at least some estimates of ice sheet collapse, thereby avoiding additional meters of sea-level rise over the next several centuries.

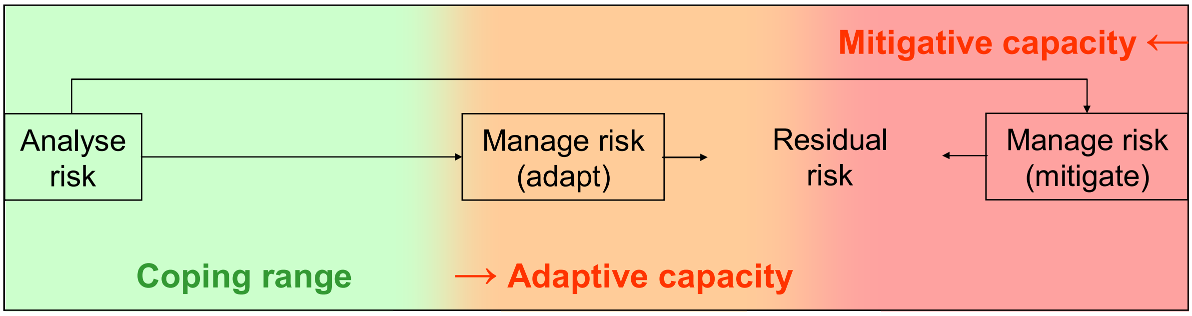

Figure 18. *Schematic representing the complementary relationship between mitigation and adaptation. Adaptive capacity expands the coping range of affected systems reducing their vulnerability, while mitigation reduces the magnitude of climate change to which systems are exposed. Thus, mitigation and adaptation approach risk from opposite directions, but collectively minimize the likelihood of a particular consequence.*

The benefits of top-down mitigation efforts for reducing impacts can be leveraged by bottom-up adaptation efforts.[122] For example, investment in public health systems and infrastructure can achieve additional reductions in climate change-related injury and mortality. Local-to-regional planning and management of water resources can assist in ensuring adequate conservation and supply for various uses. Planning of future development in the coastal zone in anticipation of sea-level rise can reduce the costs of climate change by enabling gradual retreat from advancing shorelines rather than inundation of valuable, occupied land. Successful implementation of such adaptive responses necessitates, however, extensive public education about climate change and its consequences and the provisioning of sufficient resources and investments to facilitate their implementation.

The issue of adaptation has largely been absent from the UNFCCC and the Kyoto Protocol,[123] yet adaptation can make an important contribution to avoiding "dangerous" climate change if not at the global level, then at least at the local level. The most robust method for managing the risks of climate change is to pursue GHG stabilisation mitigation and adaptation as complementary strategies (**Figure 18**).[36] Adaptation can expand the range of climate variability with which a system can cope, while mitigation reduces the upper limit of climate change to which a system will be exposed. This combination of bottom-up and top-down risk management ensures that the risk of adverse consequences is minimized.

APPENDIX I - REFERENCES

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