Garnaut Climate Change Review

Defining the impacts of climate change on extreme events

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Contents

1 Executive summary

An extreme weather or climate event, be it wind, flood, hail, bushfire, heatwave, frost, drought or rain, is an event of such intensity that it is rare in a particular place and time of year. Such events can have serious impacts on the Australian community. Tropical cyclones, floods and thunderstorms together account for more than 81% of known natural hazard deaths in Australia since 1788. Weather extremes of all kinds produced 93.6% of known building damage from disasters. The drought of 2002 alone was estimated to cost more than 40,000 jobs, decrease economic growth from 3.8% to 3.1%, and create a 50% increase in the trade deficit.

The frequency and intensity of many extremes are already changing, and in some cases these changes can be linked to increases in atmospheric greenhouse gases caused by human activities. One robust example is in the east of the continent, where the maximum temperatures have increased by about 2°C since 1957. Trends in rainfall extremes are harder to detect but in some places the trends in the long term rainfall and the rainfall extremes are not in the same direction—that is, we are truly observing 'droughts and flooding rains'. Unfortunately, the list of extremes for which we know little or nothing about is extensive, and it is generally those extremes that present the greatest risk to life and property. Insufficient work has been done to document the past history of such extremes as hail and thunderstorms, bushfires, and extreme winds.

Apart from increasing heatwaves and decreasing frost frequency, little can be said with confidence concerning the details of how extreme weather and climate events will change in the future. However, it is very unlikely that such changes will not occur. Thus as the world warms, it will be prudent to prepare for changes in heavy rainfall events, droughts, tropical cyclones, and hail and thunderstorms. Such preparation will require a whole of government approach to adaptation planning, engaging all levels from federal to local according to resources and capacity. Second, an approach that incorporates response to extremes in concert with other climate change and environmental problems, other emergency management problems, and the broader context is required. Finally, a policy process that is grounded in rigorous ongoing appraisal is more likely to leave us resilient to unexpected changes. In the truest sense, we would wish to be 'ready for anything'.

2 Introduction

Worldwide, the threefold increase in the incidence of extreme weather events from the 1960s to the 1990s was accompanied by a ninefold increase in damages (Munich Re Group 1999). Nearly 12,000 lives were lost and over 153 million lives were impacted by wind storms, wildfires, floods, temperature extremes, and droughts worldwide in 2005 alone (EM-DAT 2005). The impacts of climate and weather extremes are nowhere more apparent than in Australia in recent years.

An increasingly common extreme event is the heatwave, such as the one that occurred in eastern Australia during the period 1–22 February 2004. Maximum temperatures were 5 to 6˚C above average throughout large areas, reaching 7˚C above average in parts of New South Wales (National Climate Centre, 2004). The number of successive hot days and nights set new records. The run of nine consecutive nights above 30˚C in the rural town of Oodnadatta is without precedent in the Australian climate record. Adelaide had 17 successive days over 30˚C (the previous record was 14 days). Sydney had ten successive nights over 22˚C (the previous record was 6 nights). Around two thirds of the continent recorded maximum temperatures over 39˚C. Temperatures peaked at 48.5˚C in western New South Wales. The heatwave led to newspaper headlines such as 'Hot spell hits with collapses' (*Sunday Mail*, Adelaide, 8 February), 'Taking the heat in state of distress' (*Daily Telegraph*, Sydney, 12 February), and 'Sweltering temperatures make school children sick' (*Queensland Times*, 19 February). Brisbane recorded a temperature of 41.7˚C on the weekend of 21–22 February: that weekend the Queensland ambulance service recorded 'a 53% increase in ambulance callouts', and the ambulance service Commissioner described it as 'the most significant medical emergency in the south-east corner [of Queensland] on record' (*Canberra Times*, 24 February).

Another extreme event, Tropical Cyclone Larry, left 100 km^2 of World Heritage listed rainforest in north Queensland as 'coleslaw and sticks' in March 2006, according to the Queensland Parks and Wildlife Service (*The Age*, 11 April 2006, p 13). Thirty Queensland parks and state forests were closed or partly closed as a result of the cyclone impacts, with an estimated damage cost to the parks and reserves of $10 million. The Parks Service considered the survival (after Larry) of the southern cassowary, an endangered species, around Mission Beach, to be tenuous. Cyclone Larry caused losses of around AUS$1.6 billion and insured losses of around AUS$570 million in an area that is sparsely populated but has significant value as an agricultural and natural heritage region.

The cost of extreme weather events is rising. This is connected to increasing development in vulnerable regions as well as, in some cases such as heatwaves and bushfires, increasing frequency and severity. The droughts of 1982/83, 1991–95, and 2002/03 cost about $2.3 billion, $3.7 billion and $10 billion, respectively (adjusted to 2002–2006 values). Government drought relief averages $100 million per year. The Sydney hailstorm of April 1999 cost $2.3 billion of which $1.7 billion was insured. Not only did this hailstorm produce some of the largest hail ever recorded in Sydney, it occurred at a time of year when severe thunderstorms are normally rare and at a time of day when the storms do not usually develop or intensify (Nicholls, 2001). The 2003 Canberra bushfires caused $350 million damage. Almost 70% of the rural area of the ACT was damaged. Strong winds and high temperatures help the fire to spread into the suburbs of Canberra, where about 500 houses were destroyed, and four people killed. Large parts of the city lost power for a considerable period of time. Water, gas and landline communications were unavailable to several suburbs and mobile communications networks were overloaded. Three of the city's four dams were contaminated for several months by sediment-laden runoff.

Sometimes two or more extremes can occur simultaneously, thereby increasing the losses that result from a single extreme (Nicholls, 2008). So, high winds sometimes accompany heavy rainfall events. Heavy rainfall can weaken the hold of tree roots, thereby increasing the likelihood that a tree will be uprooted in the strong winds. Strong winds associated with cyclones may also occur at the same time that high sea levels occur, increasing the likelihood of coastal inundation. Similarly, heatwaves can cause heat-related deaths, fires, smoke pollution, respiratory illness, increased peak energy demand for air-conditioning, black-outs, increased water demand and buckling of railways. Little work has been done on the risk of such joint occurrences, whether we might expect a change in the frequency of such simultaneity of extremes in the future, or determining the impacts and costs of the joint extreme relative to a single extreme.

These are just some examples of the damage and loss of life caused by climate and weather extremes. Tropical cyclones and floods together account for more than 70% of known natural hazard deaths in Australia since 1788 (Blong, 2004). Thunderstorms account for about 11% of deaths. Meteorological extremes (tropical cyclones, floods, thunderstorms and bushfires) produced 93.6% of known building damage from disasters suggesting that non-meteorological natural hazards (such as earthquakes) present less risk overall.

Definition of extreme weather and climate events

Extremes are the infrequent events at the high and low end of the range of values of a particular climate or weather variable. In other words, an extreme weather event is an event that is rare at a particular place and time of year (IPCC, 2007a). Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function.

The characteristics of what is called extreme may vary from place to place—the temperature required to define a heatwave in Hobart would be lower than in Darwin). When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).

Although this definition appears relatively straightforward, slight differences in definitions can cause large differences in interpretation (Haylock and Nicholls 2000; Alexander et al., 2007).

Weather and climate extremes include: hot days and nights (including heat waves); cold days and nights (including frosts); heavy rainfall events; droughts; floods; hail and thunderstorms; tropical cyclones; bushfires; extreme winds.

This paper discusses what is known about how extremes are changing, the possibility that some of these changes in extremes may be attributable to anthropogenic* climate change, and projections of how extremes may change in the future. The opportunities for adaptation to changes in extremes are discussed, policy implications regarding extremes are outlined, and future research directions are indicated.

* see Glossary for this and other terms marked with an asterisk

3 Observed changes in Australian extreme weather and climate

Until recently the quality and quantity of weather data have been insufficient to allow credible examination of whether extremes are changing. Care needs to be taken to ensure that some or all of the common problems with the instrumental data used to conduct the analysis of extremes do not affect the conclusions. These problems include but are not restricted to (Nicholls et al., 2006):

- changes in site location
- changes in site condition or the local environment (e.g. growth of a tree)
- changes in instrumentation (e.g. different brand, new technology)
- changes in observing practices, including time, technique and observer training
- changes in the distribution of the network of instruments, including shutting down sites.

These changes can have *greater influence* on our documentation of extremes than on average quantities such as annual rainfall, and issues such as these meant that the Second IPCC* Assessment in 1996 reached very few conclusions regarding changes in extremes.

Since the IPCC Second Assessment in the mid-1990s, there have been increased international efforts to improve the quality and availability of data suitable for determining whether extremes have changed (Nicholls and Alexander, 2007). Because of these efforts, it is now possible to conclude that more than 70% of the global land area that was measured exhibited a statistically significant* decrease in the occurrence of extremely cold nights and a significant increase in the occurrence of extremely warm nights. Rainfall extremes showed a widespread and significant increase, but the changes vary greatly from place to place compared with the temperature changes. Other extremes such as tornadoes are much harder to monitor and it is thus much harder to determine whether or not there has been a change in their frequency and/or intensity.

Detailed analyses of trends in Australian temperature and rainfall extremes have been conducted in various studies including Collins et al (2000), Alexander et al (2007) and Gallant et al (2008). Collins et al (2000) and Alexander et al (2007) showed that maximum and minimum temperatures are increasing across most of Australia. In the east of the continent the trends in maximum and minimum temperature are up to 0.4°C per decade—a total increase of about 2°C since 1957 (Alexander et al, 2007). Consistent with this warming are statistically significant:

- decreases in cold nights and cold days
- decreases in frost days and cold spells
- increases extremely warm nights.

At any particular location, the increasing trend in the minimum temperature with concomitant less frequent cool nights is generally larger than the trend for maximum temperature and cool days. This means that the diurnal range* is decreasing. It is the increase in minimum temperature that has the most health-related impacts during heatwaves (Nicholls et al. 2007).

Alexander et al. (2007) and Gallant et al. (2008) found that the trends in rainfall extremes vary throughout the seasons. The largest trend is the significant decrease in both the average and the maximum 1-day rainfall in south-eastern Australia in March-May—the crucial Autumn break period. In some places the trends in the average rainfall and the extremes are not in the same direction (that is, we are truly observing ‘droughts and flooding rains’ in the same location). For example, the trend in the total amount of rainfall that falls on the day with the maximum rainfall is increasing almost everywhere, even in the south-west, indicating that the intensity of the rainfall is increasing. In summer, as in spring, the trends in one day maximal rainfall were increasing almost everywhere over the period 1910–2005.

Nicholls et al (2000) examined Australian trends in a wide variety of climate extremes and concluded that:

- The number of weak and moderate tropical cyclones observed has decreased since 1969 which, although consistent with changes in the Southern Oscillation Index, may be partly caused by changes in the observational system;
- The number of intense tropical cyclones has increased slightly since 1969;
- Windiness in the eastern Bass Strait has fallen, while it has increased slightly in the western Bass Strait, since the early 1960s;
- There has been a strong decrease, since 1910, in the intensity of rain falling on very wet days, and in the number of very wet days, in the south-west of the continent;
- There has been a strong increase in the proportion of annual rainfall falling on very wet days in the north-east;
- No clear trend has emerged in the percentage of the country in extreme rainfall (drought or wet) conditions, since 1910, although Burke et al (2006) reported an increase in the Palmer Drought Severity Index in south-western and eastern Australia from 1952–1998.

Unfortunately, the list of extremes for which we know little or nothing about is extensive, and it is generally those extremes that present the greatest risk to life and property. Little work has been done to document the past history such extremes as hail and thunderstorms, bushfires, and extreme winds. Where studies exist (e.g. Nicholls and Lucas, 2007; Abramson et al. 2008; Tryhorn and Lynch 2008), they are limited geographically or in time because data rescue efforts are so costly and time consuming. For many extremes, the data needed to document changes simply does not exist or is too questionable in quality to be useful. Changes in longer-lived and larger-scale extremes such as droughts and widespread flooding events are also difficult to document. For such extremes there also exists a definitional question that confounds documentation of changes. For instance, there are a plethora of definitions of 'drought' (Steinemann 2003). Which definition is relevant to a planning for future drought assistance requirements? Which definition should be used for conducting a land suitability planning exercise? And so on. Finally, there are methodological issues in addressing our understanding of extremes—that is, the statistics and dynamics of extreme events. This remains an area of active research with many possible approaches that now go beyond the extreme value theory of statistics (Katz et al. 1999), including consideration of return periods, indices that take account of frequency and duration as well as intensity, and statistical models that use multiple variables (e.g. Meehl and Tebaldi, 2004; Naveau et al. 2005; Ekstrom et al., 2005; Khaliq et al., 2005; Huth and Pokorna, 2005; Lynch et al. 2007).

4 Are these changes due to human influences on the atmosphere?

A trend towards more extremes of a particular type does not necessarily point to a human cause. A wide range of extreme weather events is possible even with a climate unaffected by human activities. Extreme weather results from a combination of factors. For example, the formation of a tropical cyclone requires warm sea surface temperatures and specific atmospheric circulation conditions. Because some factors may be strongly and directly affected by human influences, such as ocean temperatures, but others may not, this will complicate the detection of a human influence on a single, specific extreme event.

However, we may be able to determine whether our activities have changed the *probability* that an extreme weather event will occur. For example, we can study the characteristics of Queensland summers in a climate model, either driven only with historical changes in natural factors such as volcanic activity and variation in the sun, or by both human and natural factors. Such experiments may indicate whether, over the 20th century, human influences have increased the likelihood of southern Queensland temperatures as hot as those in February 2004. This was done for the northern hemisphere by Meehl and Tebaldi (2004) but to our knowledge the analysis has yet to be performed for Australia.

The value of this approach is that it can be used to estimate the influence of factors such as increases in greenhouse gas concentrations on the frequency of specific types of weather events. However, careful statistical analyses are required, since the likelihood of individual extremes could change due to changes in variability[*] as well as changes in the average climate. Such analyses rely on climate model-based estimates of the natural degree of variability in the system. Thus, an important uncertainty is the extent to which climate models adequately represent climate variability.

Based on this approach, it is possible now to argue that human influences are increasing the likelihood of heatwaves in Australia. Stott (2003) analysed simulations from a climate model for all continental regions including Australia. The model, when driven with natural and anthropogenic changes in forcing factors, did an excellent job reproducing the climate averages, trends, and variations, for the period from about 1950 to the present day. Stott's study indicated that it was the anthropogenic factors that were causing warming in Australia through the second half of the 20th century. Stott examined only mean temperatures, but extreme temperatures have been increasing similarly to mean temperatures and scaling with greenhouse gas emissions in straightforward ways (Tebaldi et al. 2006; Waterson and Dix 2005; Griffiths et al., 2005). Most recently, Alexander and Arblaster (2008) examined multiple simulations from nine global coupled climate models and assessed their ability to reproduce observed trends in a set of indices representing temperature and precipitation extremes over Australia. Observed trends over the 1957 to 1999 period were compared with modelled trends calculated over the same period. When averaged across Australia, the magnitude of trends and the variability of temperature extremes were well simulated by most models particularly for the warm nights index. Thus, evidence continues to accumulate suggests that human influences on the atmosphere are affecting these Australian extremes.

There is less clear similarity between observed and simulated changes in the frequency of heavy precipitation events over Australia, although globally there is a tendency in both observations and climate model simulations for increased frequency of heavy rainfall events at mid-latitudes. Over Australia, Alexander and Arblaster (2008) found that climate models do not agree on the magnitude of the trend in precipitation extremes, although most models do reproduce the correct sign of trend. The simulation of precipitation, over Australia as elsewhere, remains a significant challenge for the modelling community.

The same approach potentially could be adopted to examine the likelihood of changes in the frequency of extreme hydrological events such as floods. Climate models have the capacity to predict many types of extreme weather events, including an increase in extreme rainfall events, although as noted above the accuracy lags behind their capacity to predict temperature. Moreover, hydrological events are generally smaller in scale than can be represented in climate models, and depend on hydrological and ecological processes that are currently omitted from such models, and hence this is an area for future development.

Even less is known about the possible human impact on (the largely undocumented) changes in hail and thunderstorms, bushfires, and extreme winds. Such extremes are difficult to simulate in climate models, and this severely reduces our ability to determine the causes of any observed trends in such variables. The facility possessed by numerical weather prediction models and forecasting services in general is an important resource in developing our capacity for projecting these extremes into the future. Documenting and comprehensively studying the changes in such small-scale events remains a task for the future in the goal to attribute cause.

5 Projected changes in Australian climate and weather extremes

The changes in Australian extremes likely to accompany anticipated future increases in atmospheric concentrations of greenhouse gases include (CSIRO and Bureau of Meteorology, 2007; Nicholls, 2008; Alexander and Arblaster 2008):

- a continuing and stronger increase in frequency of extremely hot days and warm nights, and a concomitant increase in the frequency of heatwaves
- moderate decrease in frequency of frost, which has increased in some parts of Australia recently due to drought conditions (drier conditions can lead to cooler nights where cloud cover is decreased)
- increase in extreme rainfall events except in the southern half of the continent in winter and spring, in which case total rainfall and extreme rainfall events both decrease
- increase in the frequency and length of drought conditions, especially in southwest
- increased wind speed in most coastal areas
- conditions less favourable for cool season tornadoes in southern Australia, but hail risk may increase over southeast coastal regions
- likely increase in proportion of tropical cyclones in more intense categories, but a possible decrease in total number of cyclones
- substantial increase in fire weather risk in southeast Australia.

There is, however, considerable uncertainty in these projections, arising from the limited number of climate simulations from which they are derived, as well as model deficiencies.

Table 1 Projected changes in extremes through the 21st century, based on SRES scenarios, along with their likely impacts by sector (IPCC, 2007b)

Phenomenon[a] and direction of trend	Likelihood of future trends based on projections for 21st century using SRES scenarios	Examples of major projected impacts by sector			
		Agriculture, forestry and ecosystems {WGII 4.4, 5.4}	Water resources {WGII 3.4}	Human health {WGII 8.2, 8.4}	Industry, settlement and society {WGII 7.4}
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights	Virtually certain[b]	Increased yields in colder environments; decreased yields in warmer environments; increased insect outbreaks	Effects on water resources relying on snowmelt; effects on some water supplies	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced disruption to transport due to snow, ice; effects on winter tourism
Warm spells/heat waves. Frequency increased over most land areas	Very likely	Reduced yields in warmer regions due to heat stress; increased danger of wildfire	Increased water demand; water quality problems, e.g. algal blooms	Increased risk of heat-related mortality, especially for the elderly, chronically sick, very young and socially isolated	Reduction in quality of life for people in warm areas without appropriate housing; impacts on the elderly, very young and poor
Heavy precipitation events. Frequency increases over most areas	Very likely	Damage to crops; soil erosion, inability to cultivate land due to waterlogging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding: pressures on urban and rural infrastructures; loss of property
Area affected by drought increases	Likely	Land degradation; lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water-and food-borne diseases	Water shortage for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases	Likely	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers, potential for population migrations, loss of property
Increased incidence of extreme high sea level (excludes tsunamis)[c]	Likely[d]	Salinisation of irrigation water, estuaries and freshwater systems	Decreased freshwater availability due to saltwater intrusion	Increased risk of deaths and injuries by drowning in floods; migration-related health effects	Costs of coastal protection versus costs of land-use relocation; potential for movement of populations and infrastructure; also see tropical cyclones above

The reality of the situation is that, apart from the increases in hot days and nights, the decreases in cold days and nights and (with less confidence) increases in heavy rainfall events, little can be said with confidence, at the moment, about how extreme weather and climate events will change in the future. As noted, this is due to data scarcity, the expense of data rescue, limitations in understanding, shortfalls in model performance and problems with the definition of events. The result of this low confidence in projections is that planned adaptations to reduce our vulnerability to extremes and to enhance our emergency response and recovery processes will need to be flexible and cost-effective, in order to answer to the evolving context.

6 What will be the impact of these projected changes in extremes?

The impacts of changes in the frequency and intensity of extreme events will depend at least as much on the broader context as on the change itself—by this we mean the sectors and locations affected, the economic and policy development capacity of those sectors and locations, the other stressors that are competing for time and attentions, and legal, jurisdictional and political factors. With this caveat, it is possible to draw some very broad conclusions regarding impacts. The IPCC Fourth Assessment (IPCC, 2007b) summarised the projected changes in extremes, and their likely global impacts (Table 1). The likely impacts for Australia closely match those expected globally and so this table provides an overview of how changes in extremes may impact on Australia. More detailed Australian examples of likely impacts from projected changes in weather and climate extremes were provided by PMSEIC (2007)—see Table 2. Again, this table represents likely trends, and confidence in these projections decreases as one moves down the table.

Table 2 Examples of some projected changes in extremes likely to affect Australia, along with examples of their likely impacts (after PMSEIC, 2007)

Phenomenon	Direction of trend	Implications for Australia (examples)
Hot days and nights	↑	Less cold-stress likely to reduce lamb mortality Temperate fruits and nuts production negatively affected Increased demand for cooling; decreased demand for heating Declining summer air quality in cities
Warm spells and heat waves	↑	Increased heat stress on stock Reduced grape quality and value Increased water demand Increased threat of algal blooms Increased risk of heat-related mortality and morbidity Likely increase of water-borne and food-borne illness Reduction of electricity generation efficiency and transmission
Drought	↑	Soil erosion exacerbated Increased salinity of drinking and irrigation water supply Reduced hydropower generation Increased fire danger; duration of fire season increases.
Intense tropical cyclone activity	↑	Damage to crops and trees Power outages, leading to disruption of water supply Increased risk of deaths, injuries, water-borne and food-borne disease Major impacts for coral reefs Tourism affected

7 Opportunity to adapt to changes in extreme events

Extreme or iconic events that are related in a concrete way to the vulnerabilities of greatest concern serve as an important common focus for government, researchers and community members even as they embody different meanings (Lynch et al. 2008; Lynch and Brunner 2007). Further, the utilisation of extremes as an organising principle for enquiry engages with the new understanding that extremes often stimulate the political will to invest in climate change adaptation (e.g. Poumadère et al. 2005). The policy window opened by an extreme event is a valuable resource in the quest to reduce community vulnerabilities. As noted by economist Paul Romer: 'A crisis is a terrible thing to waste.'[1]

Internationally, the re-emergence of adaptation practices in the portfolio of responses to climate change was related to the development of the National Adaptation Programmes of Action (NAPAs), contained in Decision 5 of the 7th Conference of the Parties in Marrakesh, Morocco in early November 2001 (The 'Marrakesh Accords', UNFCCC 2001). The NAPAs were intended to focus on immediate vulnerabilities in those countries with limited adaptive capacity, and mandate a 'participatory assessment of vulnerability to current climate variability and extreme events' (UNFCCC 2007). As a result, Burton and van Aalst (2004) have observed 'a growing momentum for adaptation' with a 'diversity of sources of funding and a diversity of approaches and rules adopted by different agencies and governments.' New methods, frameworks, and guidelines are gradually being developed to facilitate adaptation programs, examples include: the United Nations Development Programme (UNDP) Adaptation Policy Framework (Burton et al., 2004), the NAPA Guidelines (UNFCCC 2002), the Assessments of Impacts and Adaptations to Climate Change (AIACC) project (AIACC 2004), and the Nairobi Work Programme (UNFCCC 2006). However, the focus has primarily been upon developing countries.

For Australia, a whole of government approach to adaptation planning, engaging all levels from federal to local according to resources and capacity, seems appropriate. A whole of government approach is recommended given that in modern Australia both effective control and detailed intelligence for decisions relevant to adapting to changes in extremes is dispersed among multiple authorities and interest groups. Further, it should be noted that efficiency is only one of many goal values to be reconciled in the policy decision process. Second, an approach that incorporates response to extremes in concert with other climate change and environmental problems, other emergency management problems, and the broader context is highly effective. This process of incorporating the broader context has sometimes been termed 'mainstreaming'.

Details regarding adaptation strategies in general are available in a companion paper by Lynch commissioned by the Garneau review. These strategies are as varied in nature as the communities and sectors affects and the extremes themselves, but will contain some common elements. Although we are unable to predict with confidence the likely changes in many types of weather and climate extremes, it is very unlikely that such changes will not occur. Thus as the world warms 4–5ºC, it will be prudent to prepare for changes to occur in heavy rainfall events, droughts, tropical cyclones, and hail and thunderstorms. Such changes could include changes in the areas most affected, or changes in the intensity of these extremes. We should anticipate that such changes will have substantial impacts, even if we cannot determine with a high degree of certainty those impacts in advance. Hence, our responses should be modest, emphasising a 'learning by doing' policy process and a 'don't bet the farm' philosophy. A modest process leaves us resilient to unexpected changes. In the truest sense, we would wish to be 'ready for anything'.

[1] As reported by Thomas L. Friedman in the New York Times on 3 April 2005.

8 Strategy and policy implications related to extreme events

Australia is a nation that has a significant history of adapting to extremes, including drought, bushfire and cyclone. These processes are, in many cases, adequate for emergency response but not for decreasing our vulnerability to increases in their incidence. For extremes whose likelihood of increase is very high and whose impacts are well understood, such as heatwaves, implementing simple adaptive responses could save many lives. In addition, such responses may shield us at least in part from the economic consequences of an increasing incidence of extremes. These consequences generally occur through losses in physical capital and infrastructure, and can result in higher costs which disadvantage some industries but benefit others.

Further, the awareness of the increasing incidence of extremes, or even the perception that this is true and associated with climate change, has the potential to impact on the Australian economy, particularly through altered consumption patterns and influence on the insurance regime. The aggregate effect of these changes in perception is generally understood to be an increase in saving and a decrease in consumption (Calzadilla et al. 2004), resulting in a different composition of demand structure in the economy and affecting regional competitiveness.

In a globalised world, extreme events happening anywhere in the world could trigger a structural adjustment throughout the global economy, with influences in Australia on productivity, trade, and capital flows. For example, the analysis of Yeo (2002) and Calzadilla (2004) suggests that while the direct impact of the 1998 floods on Australia is estimated at US$5.4b (1997 dollars) but the overall impact globally is estimated to be US$6.65b. Hence, any assessment of the economic implications of extremes, a topic for future research, will need to embrace a regional and global perspective.

9 Recommendations for future research on extreme events.

We recommend research that addresses the primary reasons for our difficulty in detecting, attributing and projecting extremes associated with anthropogenic climate change. These include:

- scholarly work and data rescue efforts to document changes, especially in localised extremes such as hail. This will require significant effort, including historical work and database development in some cases
- research on understanding the mechanisms that generate extremes and the causes of changes in extremes, including observational field work, theory and modelling
- research into the statistical methodologies that can be used to characterise extremes
- contribution to international efforts to project extremes in climate models, and engagement with numerical weather prediction and emergency services to enhance that contribution
- research on the economic, legal, cultural and social processes that present barriers to adaptation and that enhance adaptation planning
- research of the policy and decision making process, including methods of appraisal, to support implementation of adaptation solutions.

10 Conclusions

Our greenhouse gas emissions will shift our climate towards conditions that will stress our most vulnerable people and our fragile ecology. Australia's vulnerability to climate change is likely to depend more on changes in the intensity and frequency of extreme weather events than on changes in the mean climate. For many of the extremes that affect us most, little if anything is known about whether they are currently changing, the likelihood that anthropogenic climate change is causing such changes, and how they may change in the future. This is true of tropical cyclones, floods, hail, bushfires, thunderstorms, and extreme winds. The extreme events for which more information is available, and in which we have more confidence, include hot days and nights, heat waves, and (less confidently) heavy rainfall events. This lack of concrete information is partly because of difficulties in documenting, explaining and projecting extremes, and partly because of their inherently rare nature.

Nevertheless, with its historically relatively extreme weather, robust emergency management services and economic strength, Australia may be better placed than most to adapt to changes in extremes. An adaptation planning approach which incorporates the response to extremes in concert with the broader context, which admits a policy process that facilitates a strong appraisal element and which incorporates a whole of government participation and facilitation is recommended.

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12 Glossary

anthropogenic: In the context of climate change, the term anthropogenic means caused by human activities.

climate variability: The term is often used to denote deviations of climate statistics over a given period of time (such as a specific month, season or year) from the long-term climate statistics relating to the corresponding calendar period.

diurnal range: The diurnal range is the difference between the maximum temperature and the minimum temperature in one 24 hour period.

IPCC: In 1988, the United States and allied governments requested that WMO and UNEP establish an organisation that became the Intergovernmental Panel on Climate Change. The formal mandate of the IPCC was to assess available scientific information on climate change, assess the environmental and socio-economic impacts of climate change, and formulate response strategies.

statistically significant: A finding is called statistically significant if it is unlikely to have occurred by chance.