CLIMATE CHANGE AND ITS IMPLICATIONS FOR THE RUATANIWHA WATER STORAGE SCHEME

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Executive Summary

- This report discusses the basics of climate change, and global-scale climate change projections. After discussing factors that influence the New Zealand climate, climate change scenarios for New Zealand and the implications for the Hawke's Bay Region and the Ruataniwha Water Storage Scheme are described.

- Climate change projections are based on scenarios of global emissions of greenhouse gases and aerosols, assuming different social and economic futures. The A1B scenario is often taken as representative, being in many ways in the mid-range for greenhouse gas concentrations and for global mean temperature changes. The A1B scenario remains plausible, but in light of recent emissions, A1B may be conservative in terms of the magnitude of climate change by the end of the century. However, the difference between the A1B scenario and alternative less conservative scenarios is unlikely to be sufficiently significant to justify using a different basis for project planning purposes than the A1B scenario, which has been widely used to date, given the uncertainties around local-scale predictions.

- Global mean surface temperature rise is likely to be at least 3°C by the end of the 21st century (compared to the late 20th century) and may reach 4°C or more. The target agreed at the United Nations Framework Convention on Climate Change ("UNFCCC") meeting in 2009 of no more than 2°C of warming is virtually certain to be exceeded. Projected rainfall changes through this century follow a broad pattern of wetter conditions near the equator and poleward of about 45° latitude, and drier conditions in the subtropics.

- New Zealand climate is variable, controlled by the strength of the mid-latitude westerly winds, which are in turn modulated by the El Niño-La Niña cycle and the Interdecadal Pacific Oscillation.

- Rainfall changes are critically dependent on changes in the westerly winds, which are likely to increase over the country during winter and spring, and decrease during summer and autumn.

- Temperature rises of between 2° and 3°C are likely in most areas by 2100 (a rate slower than the global mean warming).

- Rainfall changes are likely to exhibit an east-west gradient associated with changes in the westerly winds.

- Rainfall is likely to increase in winter and spring (5-10% typically) in western regions by 2100, with similar-magnitude decreases in eastern and northern regions, and associated increased soil moisture deficits in eastern and northern regions.

- Rainfall is likely to decrease in summer and autumn, with increases in rainfall in eastern regions and decreases in the west and far south (magnitudes on the order of 5%). The magnitude of projected average changes is well within the range of natural variability, hence it must be borne in mind that the actual year-to-year (or decade-to-decade) sequence of change is unlikely to follow a simple linear trend.

- Climate change in Hawke's Bay is likely to be consistent with the scenarios outlined above. Temperatures across the whole region are likely to increase by 1-1.5°C by mid-century.
- Temperatures increases in Hawke's Bay of between 2° and 3°C are likely by 2100.
- Rainfall in Hawke's Bay is likely to decrease in winter and spring (up to ~5% by mid-century, and up to 10% by late century).
- Rainfall in Hawke's Bay is likely to increase slightly in summer and autumn (5-10% by late century).
- Flows from the headwaters of the Makaroro River are linked to rainfall from western regions crossing the Ruahine ranges – accordingly, small increases in winter and spring average flows and small decreases in summer and autumn flows are likely.
- The risk of heat waves and drought conditions is likely to increase significantly, while the risk of frosts and cold nights is likely to decrease. Drought risk is likely to increase most in eastern regions, including Hawke's Bay, where a doubling or tripling of the risk is likely by the end of the century. The risk of heavy rainfall events is also likely to increase, although it is likely this will not become evident in Hawke's Bay until the late 21st century.

INTRODUCTION

Personal details

My name is **James Arthur Renwick**. I am an associate professor of physical geography at Victoria University of Wellington. I teach and carry out research on all aspects of large-scale climate variability and change, focusing on the Southern Hemisphere, especially the New Zealand region and Antarctica. Prior to my present position, I was employed as a Principal Scientist for Climate Variability and Change research at NIWA (National Institute of Water and Atmospheric Research). The information provided here is given in my personal capacity as a climate scientist, not as an employee of Victoria University of Wellington.

I have a BSc (Hons) in mathematics from Canterbury University, an MSc in statistics from Victoria University of Wellington, and a PhD in Atmospheric Sciences from the University of Washington, Seattle, USA. I have around 30 years' experience in weather and climate research and prediction, with the last 15 years concentrating on climate variability and climate change research. I have wide experience of research, teaching, advice to government agencies and industry groups, and liaison within national and international scientific communities. I have 70 relevant publications in the refereed scientific literature and have written around 50 related user-specific reports.

I am Immediate Past President of the New Zealand Association of Scientists, chair of the Royal Society of New Zealand Climate Expert Panel, a member of the management committee of the Meteorological Society of New Zealand, a member of the American Meteorological Society (AMS) and of the American Geophysical Union. I am acting chair of the Landcare carboNZero Independent Advisory Panel and am a member of the World Meteorological Organisation Executive Council Panel on Polar Observations, Research and Services. I am an editor of the Journal of Climate (AMS) and on the editorial board of the International Journal of Climatology (Royal Meteorological Society).

I was a lead author for Chapter 3 (*Observations: Surface and Atmospheric Climate Change*) of Working Group I (*Climate Change 2007: The Physical Science Basis*) of the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4), and the subsequent IPCC Technical Paper on Climate Change and Water. I am currently a lead author for Chapter 14 (*Climate Phenomena and their Relevance for Future Regional Climate Change*) of Working Group I of the IPCC 5th Assessment Report (AR5). As a member of the IPCC AR4 writing team, I contributed to the IPCC receiving the 2007 Nobel Peace Prize. I was the 2005 Recipient of the Edward Kidson Medal of the Meteorological Society of New Zealand.

Scope of Report

This report discusses climate change scenarios for New Zealand and implications for the Hawke's Bay Region, in particular for the Ruataniwha Water Storage Scheme. To set the scene, it first discusses New Zealand climate, plus the basics of climate change and the science behind it. It covers the global and regional climate change projections developed in the wake of the 2007 IPCC 4th Assessment Report and outlines scientific advances since that time of relevance to New Zealand climate change scenarios.

Current observations of climate change are presented and compared to projections made since the inception of the IPCC reports in 1990. The range of climate change scenarios is outlined and the relevance of different scenarios, in light of recent greenhouse gas emissions, is discussed. The report then focuses on the eastern North Island and the region of interest for the Ruataniwha Water Storage Scheme, describing likely future climate change through the 21st century, including a discussion of changes in extreme events and associated risks.

New Zealand Climate

New Zealand lies in the middle latitudes of the southern hemisphere (34° to 47°S). The climate is affected by the band of mid-latitude westerly winds and by the subtropical high pressure belt throughout the year. Both major circulation features move north and south with the march of the seasons. The westerlies are farthest north in winter and spring and the influence of the subtropical high is strongest in summer and autumn (Figure 1). The windiest season of the year is spring, as the subtropical high begins to migrate southwards and the surface pressure gradient across New Zealand strengthens. Much of the country's weather is influenced by the passage of fronts and depressions in the westerlies, which cross New Zealand longitudes every 4-5 days at all times of the year (Maunder 1971, Sturman & Tapper 2006).

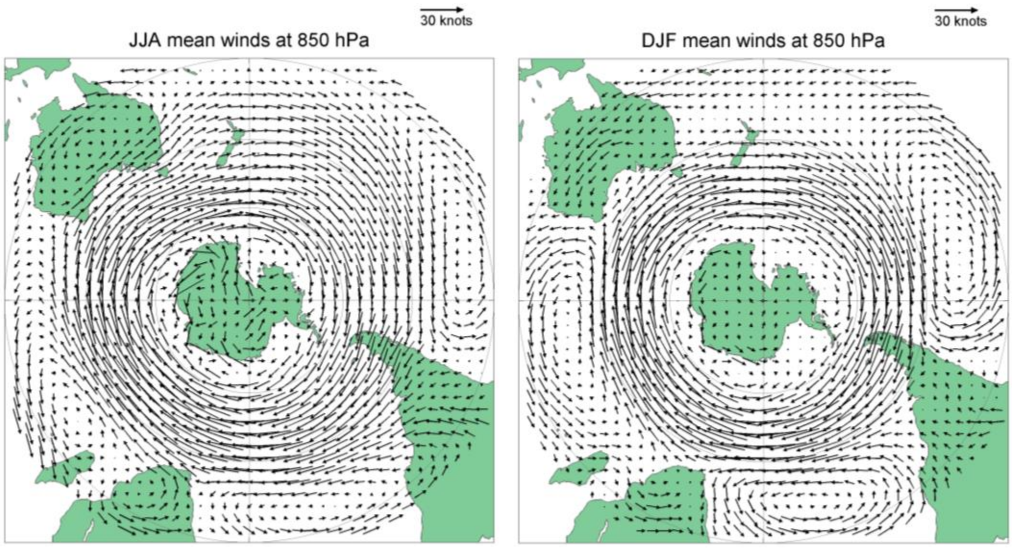

Figure 1. Southern hemisphere mean wind circulation for winter (JJA, left) and summer (DJF, right), on the 850 hPa pressure surface (approximately 1 km above ground level). Data are an average over 1971-2000 from NCEP/NCAR reanalyses (Kistler et al. 2001).

The main New Zealand mountain chains, particularly the Southern Alps, are aligned almost at right angles to the prevailing westerly wind flow and provide a significant barrier to that flow. Much of the rich regional detail in New Zealand climate comes from complex interactions between the large-scale atmospheric circulation and the rugged topography. The most notable effect is the east-west gradient in rainfall, ranging from 3 to 4 m per year in Westland to 12 m or more in the Alps, but 500 to 700 mm in Otago and Canterbury (Wratt et al. 1996; Figure 2). A similar, but weaker, gradient is seen across the southern North Island, with a relative rain shadow from Wairarapa through to Gisborne (typical annual rainfall in Wairarapa around 900 mm) and significantly larger annual rainfalls in the Tararua ranges and in parts of Taranaki (typical annual rainfall around 1500 mm or more).

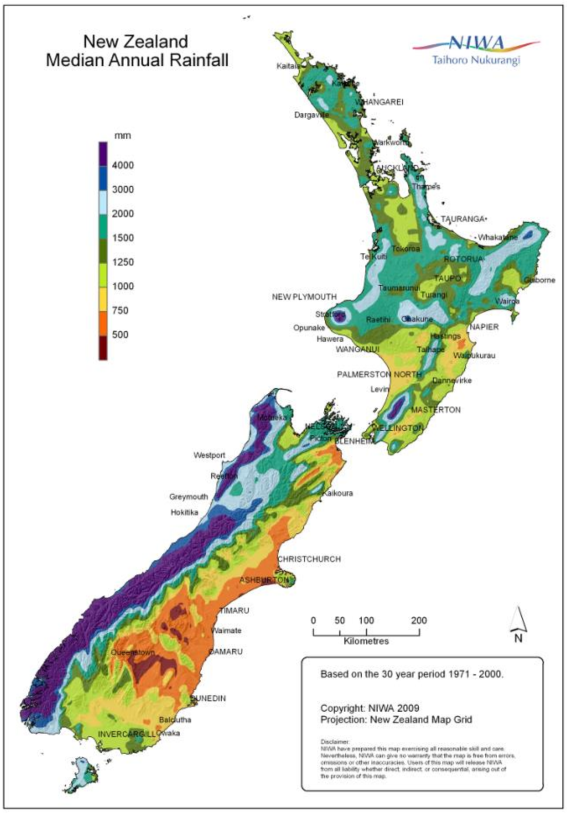

Figure 2. New Zealand median annual rainfall (mm, NIWA 2009).

Year to year variability in New Zealand climate is influenced by a number of components of the large-scale climate system, primarily through their influence on the mid-latitude westerly circulation that defines much of the country's climate. The most notable are the El Niño-Southern Oscillation (ENSO) cycle (Gordon 1986, Mullan 1996) and the Interdecadal Pacific Oscillation (IPO; Salinger et al. 2001).

The ENSO cycle between El Niño and La Niña is an irregular seesaw of heat, wind and rainfall across the tropical Pacific Ocean. Such tropical shifts have flow-on effects across the Pacific, resulting in changes in winds, temperatures and rainfalls across New Zealand. During an El Niño, when the eastern tropical Pacific warms and the trade winds weaken, New Zealand experiences (on average) cooler conditions with stronger westerly winds. Rainfall tends to increase in western regions, with an increased risk of dry conditions in the east and north. During a La Niña, when the eastern tropical Pacific cools and the trade winds strengthen, New Zealand experiences (on average) reduced westerly winds, with warmer conditions, especially over the summer months. Rainfall is on average enhanced in the north and east, and reduced in the west and south. Rainfall variations associated with ENSO are typically in the range 5 to 20% of normal.

The IPO is essentially a long-term modulation of the ENSO cycle, bringing 20-30 year periods of stronger and more frequent El Niño events, alternating with periods of weaker El Niño and stronger La Niña conditions. The IPO is manifested as a change in the background state of the Pacific Ocean, moving towards an El Niño state during the positive phase (e.g., late 1920s to mid–1940s, late 1970s to late 1990s), and towards a La Niña state during the negative phase (e.g., late 1940s to mid-1970s, and since 2000). During the positive IPO, with a predominance of El Niño events, New Zealand tends to experience generally stronger westerly wind flow, with higher mean rainfalls in western and alpine regions (around 10% higher than the long-term mean). During the negative IPO, the mean westerly circulation over New Zealand slackens, and rainfalls tend to reduce in western regions, while increasing somewhat in the northeast of the country.

OUTLINE OF CLIMATE CHANGE SCIENCE

The average surface temperature of the earth is controlled by the balance of incoming solar energy (light) absorbed at the earth's surface against outgoing infrared energy (heat). The atmosphere is largely transparent to solar energy, but strongly absorbs infrared energy radiated up from the earth's surface, through the action of 'greenhouse gases'. Naturally-occurring greenhouse gases (GHGs), including water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3), absorb heat within the lower atmosphere and re-radiate some of that heat back to the surface of the earth, leading to higher temperatures at the surface than would be the case if they were absent, the so-called 'natural greenhouse effect'. The Earth's natural greenhouse effect makes life as we know it possible[1].

Changes to the earth's surface temperature require a change to the amount of incoming solar energy or a change to the amount of outgoing infrared energy. An increase of greenhouse gas concentrations above natural levels enhances the greenhouse effect, thereby changing the radiation balance of the Earth. Changes in the amount or distribution of incoming solar radiation reaching the earth, in the fraction of solar radiation that is reflected (e.g. by changes in cloud cover, atmospheric aerosol particles, or surface vegetation) or in the outgoing thermal radiation (e.g. through changing greenhouse gas concentrations) alters the Earth's radiation balance. The climate system, in turn, responds directly to such changes, as well as indirectly through a variety of feedback mechanisms[2]. A significant increase in greenhouse gas concentrations in the atmosphere would lead to further warming (above the natural greenhouse warming) and would induce other changes in the global climate system.

As noted above, warming may be induced by an increase in solar output, or by a decrease in the fraction of incoming sunlight that is reflected back into space (referred to as the albedo of the planet). Some authors have suggested that the recent warming trend may be due to increased solar activity (e.g. Usoskin et al. 2005). However, the solar hypothesis is not supported by observations, especially over the past 50 years, where there have been no significant trends in solar activity (apart from the small variations in solar intensity associated with the 11-year "sunspot cycle") while global mean surface temperatures have risen significantly (e.g. Benestad and Schmidt 2009). Over the past several decades, the only significant change that has been observed in the factors affecting the global energy balance is in the concentration of greenhouse gases in the atmosphere. Hence, the emphasis here is placed upon human-induced greenhouse gas-related effects upon the climate system.

The greenhouse effect and the effects of increasing greenhouse gas levels have been understood for over a century. Some of the key scientific papers on the natural and the enhanced greenhouse effect include Tyndall (1863a,b), Arrhenius (1896), Callendar (1938), Kaplan (1952), Revelle and Suess (1957), Bolin and Eriksson (1959), Manabe and Wetherald (1967) and Sundquist (1987). A comprehensive summary of the history and the physics of human-induced climate change is given by Weart (2003).

[1] *IPCC Fourth Assessment Report, Working Group I, Frequently Asked Question 1.3*
[2] *IPCC Fourth Assessment Report, Working Group I, Frequently Asked Question 1.1*

The Intergovernmental Panel on Climate Change (IPCC)

In 1988 the IPCC was established by the United Nations Environment Programme and the World Meteorological Organization. Its role is to assess, on a comprehensive, objective, open and transparent basis, the latest scientific, technical and socio-economic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts and options for adaptation and mitigation[3]. IPCC assessment reports have provided key inputs to the development of the UNFCCC and the Kyoto Protocol.

The IPCC provides comprehensive Assessment Reports once every 5 to 7 years, plus Special Reports and Technical Papers. Their comprehensiveness is achieved through contributions from experts in all regions of the world and all relevant disciplines, and through a two-stage review process by experts and governments. This means the IPCC provides the most complete and authoritative assessments of climate change that are available.

The most recent IPCC assessment, Climate Change 2007: The Fourth Assessment Report ('AR4') drew on the expertise of more than 450 lead authors, 800 contributing authors, and 2,500 scientific expert reviewers from over 130 countries. Much of the material in this report is based on the Fourth Assessment Report and subsequent New Zealand-focused reports, with updates where appropriate.

Since the AR4 was published, there have been many attacks upon the science of climate change. A particularly significant event was "climategate" in 2009, where a large number of emails were stolen from the University of East Anglia Climate Research Unit (CRU) and were circulated around the internet. Parts of some emails were construed as evidence of fraud, where it was claimed that data were manipulated to show spurious evidence of warming. The head of the CRU, Dr Phil Jones, stood aside while investigations were carried out.

The most recent investigation, chaired by Lord Oxburgh of Liverpool[4], cleared Dr Jones and his research group of any wrong-doing. The report stated that there was "no evidence of any deliberate scientific malpractice in any of the work of the Climatic Research Unit". However, they did comment that the CRU were a group of "dedicated if slightly disorganised researchers" with "rather informal" internal procedures. Moreover, the investigation noted that "it is very surprising that research in an area that depends so heavily on statistical methods has not been carried out in close collaboration with professional statisticians". After the release of the report, Lord Oxburgh was quoted as saying[5] the investigation found "absolutely no evidence of any impropriety whatsoever". However, in light of such reports, and a subsequent Inter-Academy Council Review of the IPCC[6], a number of changes have been made to procedures for the AR5 to help ensure transparency and consistency.

[3] *http://www.ipcc.ch/about/index.htm*
[4] *http://www.uea.ac.uk/mac/comm/media/press/CRUstatements/SAP*
[5] *http://www.guardian.co.uk/environment/2010/apr/14/oxburgh-uea-cleared-malpractice*
[6] *http://reviewipcc.interacademycouncil.net/*

Emissions scenarios

The extent of future climate change depends in large part on future concentrations of atmospheric greenhouse gases and aerosols. Much of the recent work on projections of climate change has been based around the so-called 'SRES' scenarios, named after the Special Report on Emissions Scenarios published by the IPCC (Nakicenovic et al. 2000). Note that none of the SRES scenarios consider additional policy-driven interventions (such as those considered in United Nations Framework Convention on Climate Change (UNFCCC) negotiations) to constrain anthropogenic greenhouse gas emissions. The SRES scenarios are based on a set of possible socio-economic and technological futures, broken into two broad families (Figure 3). The "A" scenario family is more focused on economic and market considerations, while the "B" scenarios are more focused on the natural environment and sustainability. Within each family, scenarios numbered "1" feature global action while those numbered "2" feature more regional or local action with less international cooperation.

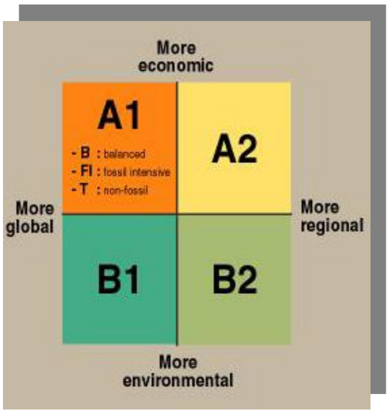

Figure 3: Schematic of the different families of IPCC SRES emissions scenarios.

Within A1, three main scenario types have been used: 'B' for balanced (between clean technology and use of fossil fuels), 'T' for a non-fossil and more green-technology future, and 'FI' for fossil-intensive (sometimes labelled the 'business as usual' scenario). While none of the scenarios is considered more likely than any other, the A1B scenario is considered close to a middle path, while B1 is a very 'clean and green' future and A1FI is a future where all available fossil fuel resources are exploited.

In the AR4, the range of global mean temperature increase during the 21st century was given as 1.1–6.4°C, over the six SRES 'illustrative scenarios' (Figure 4). The A1B scenario is often referred to here, representing a middle-of-the-road future. Projections based on the A1B scenario result in mid-range changes in global mean temperatures and other climate parameters. Using the A1B scenario, global mean warming is projected to average just under 3°C by the end of this century, relative to the late 20th century (or about 3.5°C relative to pre-industrial temperatures). For comparison, under the A2 scenario, global mean warming is projected to average just over 3.5°C by the end of this century, relative to the late 20th century (around 4.2°C relative to pre-industrial temperatures).

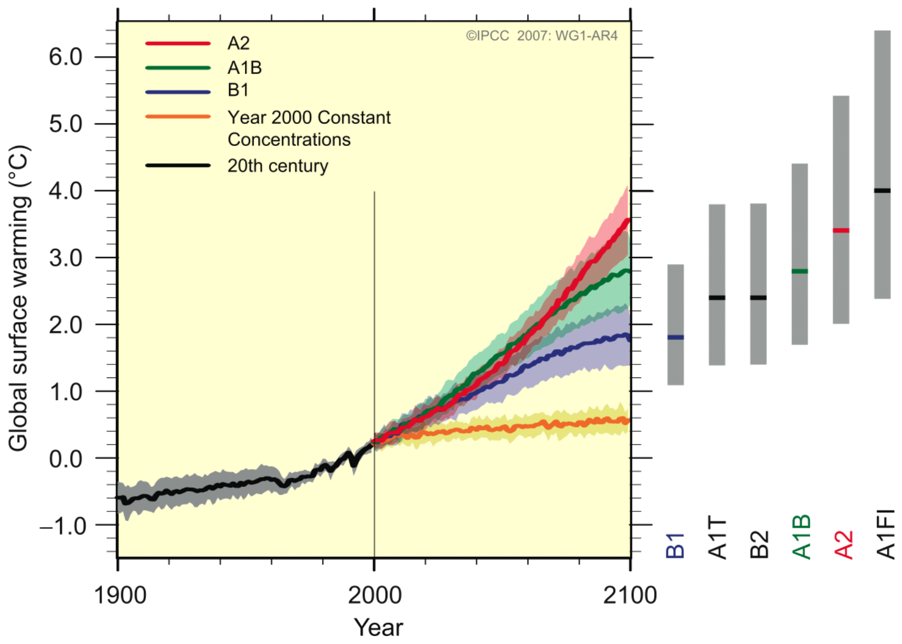

Figure 4. Global mean surface warming for a range of six emissions scenarios and climate models. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B, and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line (bottom line) is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid coloured line within each bar) and the likely range of warming by 2100 for the six SRES marker scenarios. (Source: figure SPM.5, IPCC 2007).

Note that in Figure 4, and with climate change projections generally, another source of uncertainty is associated with the global climate models (GCMs) used to project future climate changes. While many models agree on the general patterns of change, the magnitude of changes varies between models, especially regionally, and in the case of regional rainfall changes even the sign of some changes can differ between models. Here, results are presented as averages across a number of climate models, with estimates of model-related uncertainty given where appropriate.

While the information presented here represents our best understanding, climate change science continues to evolve. The projected magnitude and scope of future climate change is continually being adjusted to account for new findings such as the effect of terrestrial biogeochemical feedbacks in the climate system (Arneth et al. 2010), and for refinements in climate models.

OBSERVED CLIMATE CHANGES AND RECENT RESEARCH

Atmospheric concentrations of the greenhouse gases carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750. They now far exceed pre-industrial values (Etheridge et al. 1996, MacFarling Meure et al. 2006, Manning et al. 1997, Forster et al. 2007) and are higher than they have been for millions of years.

Recent anthropogenic carbon dioxide emissions from fossil fuel use have been towards the upper end of the range assumed for the SRES scenarios considered in the Fourth Assessment Report (Van Vuuren and Riahl 2008; Raupach et al. 2009; Manning et al. 2010). The global atmospheric concentration of carbon dioxide stood at 393 parts per million (ppm) in November 2011[7] (40% above the pre-industrial value of 280 ppm).

The AR4 concluded with very high confidence[8] that the globally averaged net effect of human activities since 1750 has been one of warming[9]. Most of the observed increase in global average temperatures since the mid-20th century is very likely[10] a result of the observed increase in greenhouse gas concentrations (from human emissions). Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns[11].

Global average annual surface temperatures in the past decade have been at historical highs, with 2010 and 2005 tied for warmest recorded year, followed by 1998[12]. The first decade of the 21st century was the warmest since the instrumental record began. Recent work (Meehl et al. 2009) indicates that high temperature extremes are presently increasing at twice the rate of low temperature extremes and this ratio is expected to continue to increase into the future. Frame and Stone (2012) showed that the rate of global mean temperature increase observed over the past 20 years matches well with what was expected in the first IPCC Assessment published in 1990.

Global average sea level rose at an average rate of 1.8mm per year [uncertainty range 1.3 to 2.3[13] mm per year] over 1961 to 2003. The rate was faster over 1992 to 2003: about 3.1 [2.4 to 3.8][14] mm per year. Whether the faster rate reflects decadal variability or an increase in the longer term trend is unclear[15]. The total 20th century sea level rise is estimated to be 170 [120 to 220] mm[16]. Recent work (Jevrejeva et al. 2009, Merrifield et al. 2009) indicates that human-induced increases in greenhouse gas levels are the main driver of sea level rise over the past 150 years and that the rate of sea level rise has accelerated (approximately

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[7] *http://www.esrl.noaa.gov/gmd/ccgg/trends/*

[8] *Very high confidence represents at least a 9 out of 10 chance.*

[9] *Climate Change 2007: The Physical Science Basis Summary for Policy Makers page 3.*

[10] *Very likely indicates a likelihood of more than 90%*

[11] *Climate Change 2007: The Physical Science Basis Summary for Policy Makers page 10.*

[12] *http://www.ncdc.noaa.gov/sotc/global/2011/13*

[13] *These uncertainty ranges represent 90% uncertainty levels, that is, there is an estimated 5% likelihood that the value could be below 1.3 mm / year, and a 5% likelihood it could be above 2.4 mm/yr. The best estimate is 1.8 mm/year.*

[14] *As before, the numbers in square brackets represent the 90% uncertainty range.*

[15] *Climate Change 2007: The Physical Science Summary for Policymakers page 5*

[16] *Climate Change 2007: The Physical Science. Summary for Policymakers page 7.*

doubled) in recent decades. Recent sea level rise has continued to track near the upper end of the AR4 projections (Rahmstorf et al. 2007, Merrifield et al. 2009)[17]. Recent work (Pfeffer et al. 2008; Alley et al. 2008) suggests that total sea level rise of up to 2 metres is physically possible this century, but it is more plausible that accelerated ice loss could lead to total sea level rise by 2100 of up to 1 metre. A recent study (Robinson et al. 2012) suggested that the threshold for irreversible melting of the Greenland Ice Sheet may be a warming of less than 2°C, considerably lower than previously thought.

The end-of-summer extent of Arctic sea ice has continued to decline rapidly (considerably faster than projected), with the extent in September 2012 being the lowest since satellite-based observations began in 1979, followed by 2007 and 2008[18]. The trend in September sea ice extent in the Arctic is now a 13% per decade decrease. Since 1979 there has been close to a 50% decrease to total Arctic end-of-summer sea ice extent. Antarctic sea ice extent has increased by about 5% in winter over the past 30 years, mostly around the Ross Sea region, as a response to changes in wind flows around the continent.

There is a growing recognition that the severity of anthropogenic climate change depends on whether the changes can be reversed (as well as on the magnitude of such changes). Solomon et al. (2009) have shown that climate change that takes place due to increases in carbon dioxide concentration is largely irreversible for at least 1,000 years after emissions stop. The trajectory of greenhouse gas emissions over the past decade suggest that the target agreed to at the 2009 Copenhagen UNFCCC meeting of limiting global warming to no more than 2°C above pre-industrial temperatures is virtually certain to be exceeded (Meinshausen et al. 2009). A global mean surface temperature rise of at least 4°C by the end of this century is now looking likely (Anderson and Bows 2008, 2011).

These observations and science developments strengthen the "reasons for concern" regarding the impact of anthropogenic greenhouse gas emissions provided in the AR4.

PROJECTED FUTURE CLIMATE CHANGES

Global changes

Continued greenhouse gas emissions at current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century[19]. For the next two decades a warming of about 0.2°C per decade is projected for a range of emission scenarios. Even if

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[17] *"Key Message 1 – Climatic Trends" in: University of Copenhagen Synthesis Report from Climate Change - Global Risks, Challenges and Decisions. Copenhagen 2009, 10-12 March. www.climatecongress.ku.dk. Pages 8-11.*

[18] *http://nsidc.org/arcticseaicenews/2012/10/poles-apart-a-record-breaking-summer-and-winter/ Figure 3*

[19] *Climate Change 2007: The Physical Science Basis Summary for Policy Makers page 13*

the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected[20]. These rates of change do not take account of the effects of natural variability such as ENSO and the IPO.

The AR4 considered six SRES scenarios, all of which give different projections based on a range of variables. The best estimates for global average surface warming at the end of this century (difference in mean global temperature from 1980-99 to 2090-99) under the six scenarios range from 1.8°C to 4.0°C, as shown in Table 1 below. Table 1 also shows the projected global average sea level rise under each of the six scenarios over the same period. The projections range from 0.18 m to 0.59 m relative to 1980 to 1999[21].

Other major changes associated with climate change are projected to include:

- contraction of snow cover;
- shrinking of sea-ice in both the Arctic and Antarctic;
- (very likely) an increased frequency of extreme hot days, heat waves and heavy precipitation events;
- changes in precipitation patterns;
- increasing acidification of the ocean over the 21st century, adding to the change that has already occurred since pre-industrial times[22]; and
- based on a range of model projections, it is likely that in future tropical cyclones will become more intense[23].

[20] *Climate Change 2007: The Physical Science Basis 10.3, 10.7 (Summary for Policymakers pg 12 para 5)*

[21] *The projections do not include uncertainties in climate-carbon cycle feedbacks or the full effects of changes in ice sheet flow, therefore the upper values of the ranges are not to be considered upper bounds for sea level rise. In the longer term, the eventual contributions to sea level rise from Greenland ice sheet loss could be several metres, and larger than from thermal expansion, should warming in excess of 1.9 to 4.6 °C above pre-industrial levels be sustained over many centuries.*

[22] *Climate Change 2007: The Physical Science Basis Summary for Policy Makers page 14*

[23] *Climate Change 2007: The Physical Science Basis Summary for Policy Makers pages 15-16*

Table 1 - Table SPM.3 from the Fourth Assessment Report: Projected global average surface warming and sea level rise at the end of the 21st century.

Case	Temperature Change (°C at 2090-2099 relative to 1980-1999)[a] Best estimate	Likely range	Sea Level Rise (m at 2090-2099 relative to 1980-1999) Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations[b]	0.6	0.3 - 0.9	N/A
B1 scenario	1.8	1.1 - 2.9	0.18 - 0.38
A1T scenario	2.4	1.4 - 3.8	0.20 - 0.45
B2 scenario	2.4	1.4 - 3.8	0.20 - 0.43
A1B scenario	2.8	1.7 - 4.4	0.21 - 0.48
A2 scenario	3.4	2.0 - 5.4	0.23 - 0.51
A1FI scenario	4.0	2.4 - 6.4	0.26 - 0.59

a These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth System Models of Intermediate Complexity and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs).

b Year 2000 constant composition is derived from AOGCMs only.

The distribution of future global warming is likely to be non-uniform, with the largest warming projected over the Arctic and the high-latitude continents of the Northern Hemisphere (Hansen et al. 2006; 2007, Meehl et al. 2007). The least surface warming is projected to occur over the southern oceans (Figure 5). As the world warms, the tropical regions expand (as has already been observed, e.g. Seidel et al. 2007), leading to significant large-scale changes in rainfall patterns globally. Broadly, increased rainfall is projected in regions near the Equator and over middle and high latitudes of both hemispheres, while subtropical regions (mostly between 30° and 40° latitude) are projected to see decreased rainfall as the subtropical high pressure belt spreads poleward (IPCC 2007, Figure 6). The global hydrological cycle is expected to accelerate with climate change (Wentz et al. 2007) and global evaporation has been predicted to increase (Ramanathan 2001). As the average climate changes, the frequency and intensity of extremes is also projected to change, often more rapidly than the change in the mean climate (Easterling et al. 1997, 2000).

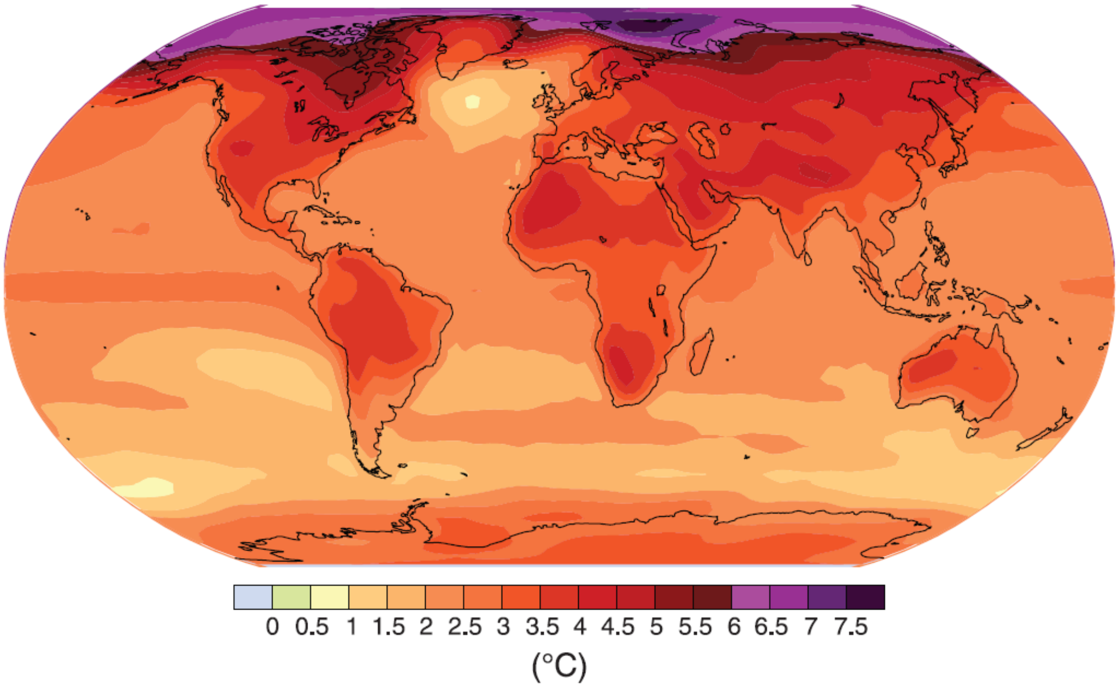

Figure 5: Average annual mean temperature change for 2080-2099 compared to 1980-1999. Results are a multi-model mean using the A1B emissions scenario. From the AR4 Summary for Policymakers, Figure SPM.6.

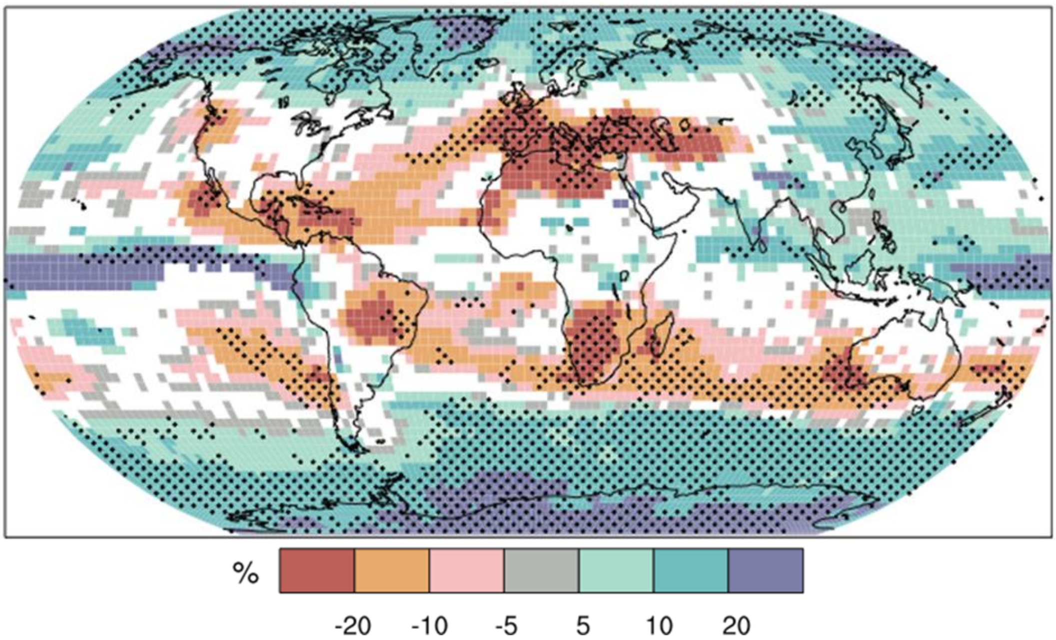

Figure 6: Average southern winter (June-Aug) mean rainfall change for 2080-2099 compared to 1980-1999 (in percent). Results are a multi-model mean using the A1B emissions scenario. Stippled areas are where more than 90% of models agree on the sign of change, and white where less than 66% of models agree on the sign of change. From the AR4 Synthesis Report, Figure 3.3.

Climate change will continue to have a range of effects into the future, which will likely increase in intensity over time. The extent of these effects will depend on the extent of warming over the course of the century. This is shown in Figure 7, reproduced from the AR4 Synthesis Report[24,25]. The temperature rises projected by the end of the 21st Century for the six SRES emissions marker scenarios are shown at the base of the diagram.

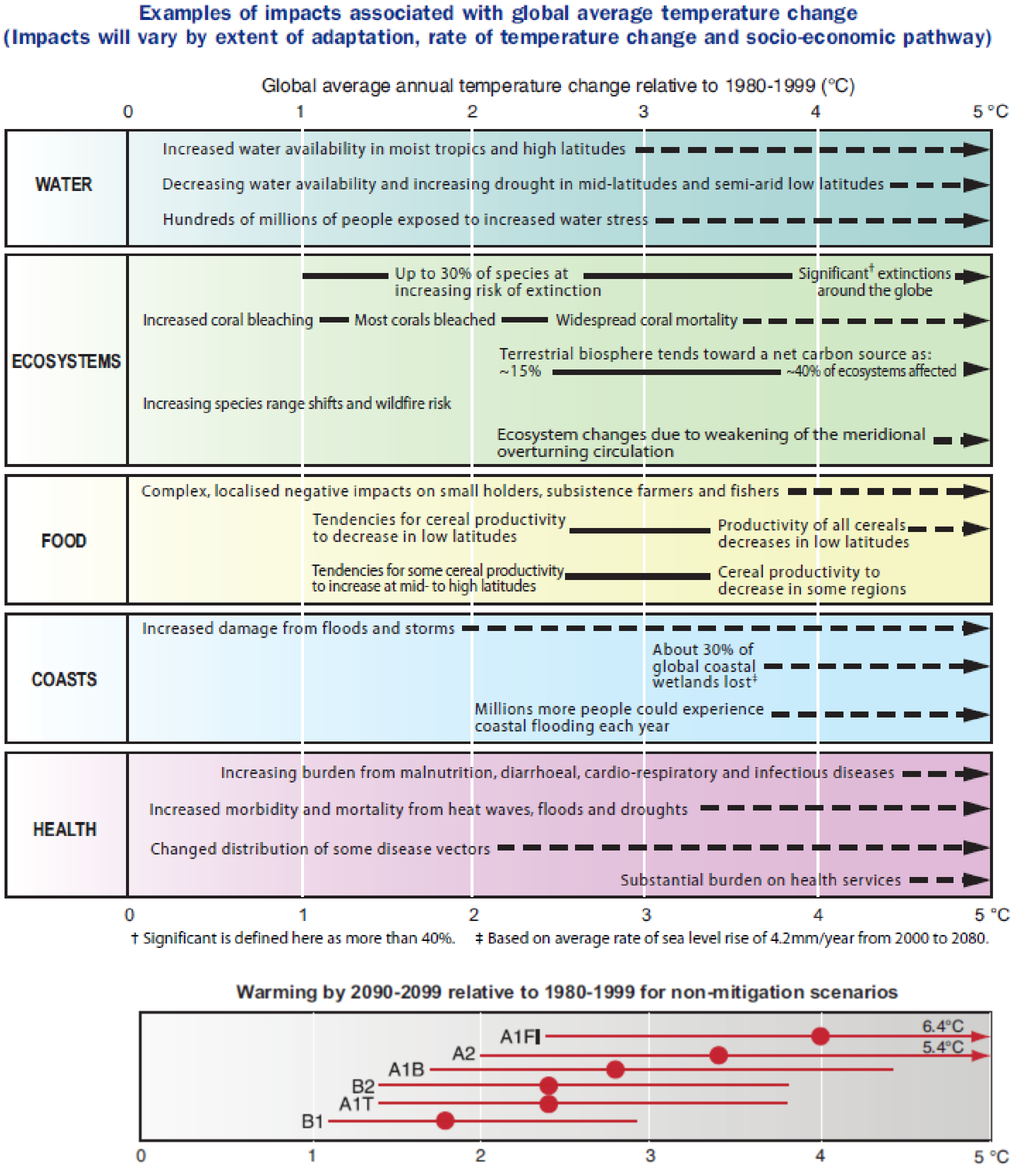

Figure 7 - Figure SPM.7. from the Fourth Assessment Report

Some of the potential future effects of climate change shown in Figure 7 are:

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[24] *http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html*

[25] *Climate Change 2007: Synthesis Report. Figure SPM.7, page 10.*

- Approximately 20-30% of plant and animal species assessed are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.5°C[26] (medium confidence);
- A 1 to 2°C increase in global mean temperature above 1990 levels (about 1.5°C to 2.5°C above pre-industrial levels) poses significant risks to many unique and threatened systems including many biodiversity hotspots[27];
- Humans are also likely to face mounting difficulties in some regions. For example Figure 7 suggests a rise in global mean annual temperature relative to 1980-1999 of just 1°C would lead to hundreds of millions of people becoming exposed to:
    - increased water stress;
    - a tendency for cereal productivity to decrease in low latitudes;
    - increased damage from floods and storms;
    - an increasing burden from malnutrition, diarrhoeal, cardio-respiratory and infectious diseases; and
    - increased morbidity and mortality from heat waves, floods and droughts.

The pattern of change in temperature and rainfall is illustrated in Figures 5 and 6. As has been already observed, temperatures are projected to rise fastest in the high northern latitudes and slowest over the southern oceans.

Changes in extreme events

As the average climate changes, the risks of extreme events (heat waves, floods, droughts, coastal inundation and so on) also change, often much more quickly than the change in average climate. A new IPCC Special Report on extremes (SREX, IPCC 2012) discusses changing risks of extremes in detail.

The changing risks of extremes associated with a shift in the mean climate are illustrated in Figure 8. A modest increase in average temperatures that is well within the range of present observations can result in a large increase in the frequency of occurrence of extreme hot days, and the occurrence of new record high temperatures. Rainfall changes are associated with more complex changes in rainfall distributions, with simultaneously increased probability of heavy rainfall and of very dry or drought conditions. Increases in maximum rainfall amounts are likely to follow the relationship between temperature and atmospheric moisture content, where for every 1°C rise in temperature, the maximum atmospheric moisture content increases by 7-8% (Mullan et al. 2008). In broad terms, a 2°C average warming over New Zealand is likely to lead in many places to an approximate halving of the

[26] *Climate Change 2007: Impacts, Adaptation and Vulnerability 4.4, Table 4.1 (Summary for Policymakers pg 11 para 9)*

[27] *Climate Change 2007: Synthesis Report. Page 19*

average return interval of most rainfall extremes over the coming century (e.g. the 1-in-100 year 24-hour rainfall is likely to become the 1-in-50 year event by the end of the century).

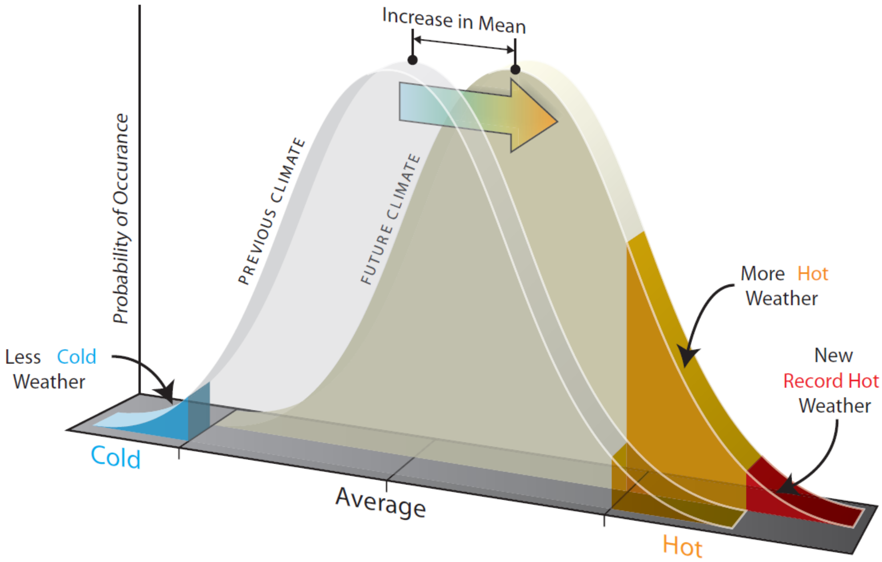

Figure 8: Schematic showing changes in the occurrence of extremes for a shift in the average climate. The diagram shows a probability distribution of temperatures under a reference climate and for a future climate shifted towards higher average temperatures. There is a significant increase in the occurrence of hot weather, even though the increase in mean temperature is well within the typical range of temperatures experienced under the reference climate conditions. The same shift results in a significant decrease in the occurrence of extreme cold weather (e.g., frosts). From Reisinger et al. (2010).

Appropriateness of the A1B scenario for future projections

The A1B emissions scenario is often used as a representative 'middle of the road' scenario for climate change this century, as noted above. The A1B scenario is associated with a projected global mean surface temperature rise of around 3°C. Given recent analysis suggesting that 4 degrees of global warming is quite likely this century, and given that greenhouse gas emissions and some aspects of observed climate change are proceeding at the upper end of expectations, A1B may be a considered a conservative scenario. Yet it is one that remains plausible and does represent a possible future for the 21st century. Furthermore, the patterns of change, in terms of temperature and rainfall seen in Figures 5 and 6, vary only slightly across a range of scenarios, the main difference being only the magnitude of projected changes. Hence the patterns of change captured in A1B scenarios are likely to be representative, even though the magnitude of change may be conservative. It is difficult to comment on what magnitude of change would be most realistic, but the difference is unlikely to be sufficiently significant to justify using a different basis for project planning purposes than the A1B scenario, which has been widely used to date[28], given the uncertainties around local-scale predictions.

Since the AR4, a new range of scenarios has been developed, known as Representative Concentration Pathways (RCPs, van Vuuren et al. 2011). Model projections for the 5th Assessment Report (AR5) are based on RCPs rather than SRES scenarios. Although the philosophy for development of RCPs is different to that of SRES, the range of RCPs overlaps strongly with the range of SRES scenarios. The A1B scenario lies near the middle range of the RCPs, in terms of associated greenhouse gas concentrations and emissions pathways.

New Zealand climate change

Just as there is no doubt that climate change is occurring, there is also no doubt that it is having an effect on New Zealand. Mean air temperatures have increased by around 1.0°C in the past century[29]. Local sea surface temperatures rose by 0.7°C between 1871 and 1993[30]. From 1951 to 1996, the number of cold nights and frosts (the coldest 5% of nights over the period) declined by 10-20 days, a decrease of around one third at many locations[31]. Global warming will continue to have an effect on New Zealand's climate, which is virtually certain (at least 99% probability) to become warmer through the 21st century, with changes in extreme events. Floods, landslides, droughts and storm surges are very likely (at least 90% probability) to become more frequent and intense, but snow and frost are very likely to become less frequent. Large areas of eastern New Zealand are likely to experience lower soil moisture, although western New Zealand is likely to receive more rain[32]. Based on global model projections, for New Zealand as a whole, a rise in average temperatures of 0.1 to 1.4°C is likely by the 2030s and 0.2 to 4.0°C by the 2080s[33]. Multi-model average annual mean changes in temperature and rainfall for New Zealand are shown in Figure 9 for mid-century and in Figure 10 for the late 21st century, for the A1B emissions scenario[34].

Changes in mean climate will in turn have major flow-on effects. As a result of reduced precipitation and increased evaporation, water security problems are projected to intensify by 2030 in Northland and some eastern regions. Rain events are likely to become more intense when they occur, leading to greater storm runoff. This is likely to cause greater erosion of land surfaces, more landslides, redistribution of river sediments, and a decrease

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[28] *e.g. MfE Guidance Manual for Local Government, Mullan et al. (2008).*

[29] *http://www.niwa.co.nz/climate/nz-temperature-record*

[30] *Folland, C.K. and Salinger, M.J., 1995: Surface temperature trends in New Zealand and the Surrounding Ocean, 1871-1993. International Journal of Climatology 15, 1195-1218.*

[31] *Climate Change 2007: Impacts, Adaptation and Vulnerability 11.2.1*

[32] *Climate Change 2007: Impacts, Adaptation and Vulnerability. Chapter 11 (Australia and New Zealand), Section 11.3.1*

[33] *Climate Change 2007: Impacts, Adaptation and Vulnerability. Chapter 11 (Australia and New Zealand), Section 11.3.1*

[34] *http://www.niwa.co.nz/our-science/climate/information-and-resources/clivar/scenarios*

in the protection afforded by levees[35]. New Zealand is already vulnerable to weather extremes. Of the total NZ$1.5billion (adjusted to 2004 dollars) of New Zealand insurance payouts for natural hazards between 1968 and 2004, approximately 75% was for weather-related losses (Wratt et al. 2006).

On-going coastal development and population growth in coastal areas, especially in eastern regions, are projected to exacerbate risks from sea-level rise and storm surge events[36]. Regional and seasonal details of changes in storm surge risk remain uncertain, as a consequence of uncertainties over regional changes in storminess.

Production from agriculture and forestry is projected to decline by 2030 over parts of eastern New Zealand, due to increased drought and fire risk. However, initial benefits to agriculture and forestry are projected in western and southern areas, and close to major rivers, due to a longer growing season, less frost and increased rainfall[37]. In the longer term, agricultural systems are likely to become increasingly vulnerable to climate changes as temperatures rise, with increased incidence of invasive pests, lower-yield pastures and a tendency towards declining pasture production (MfE 2001).

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[35] *Climate Change 2007: Impacts, Adaptation and Vulnerability. Chapter 11 (Australia and New Zealand), Section 11.4.1.2*

[36] *Climate Change 2007: Impacts, Adaptation and Vulnerability. Chapter 11 (Australia and New Zealand), Section 11.4.5, 11.4.7.*

[37] *Climate Change 2007: Impacts, Adaptation and Vulnerability. Chapter 11 (Australia and New Zealand), Sections 11.4.3, 11.4.4.*

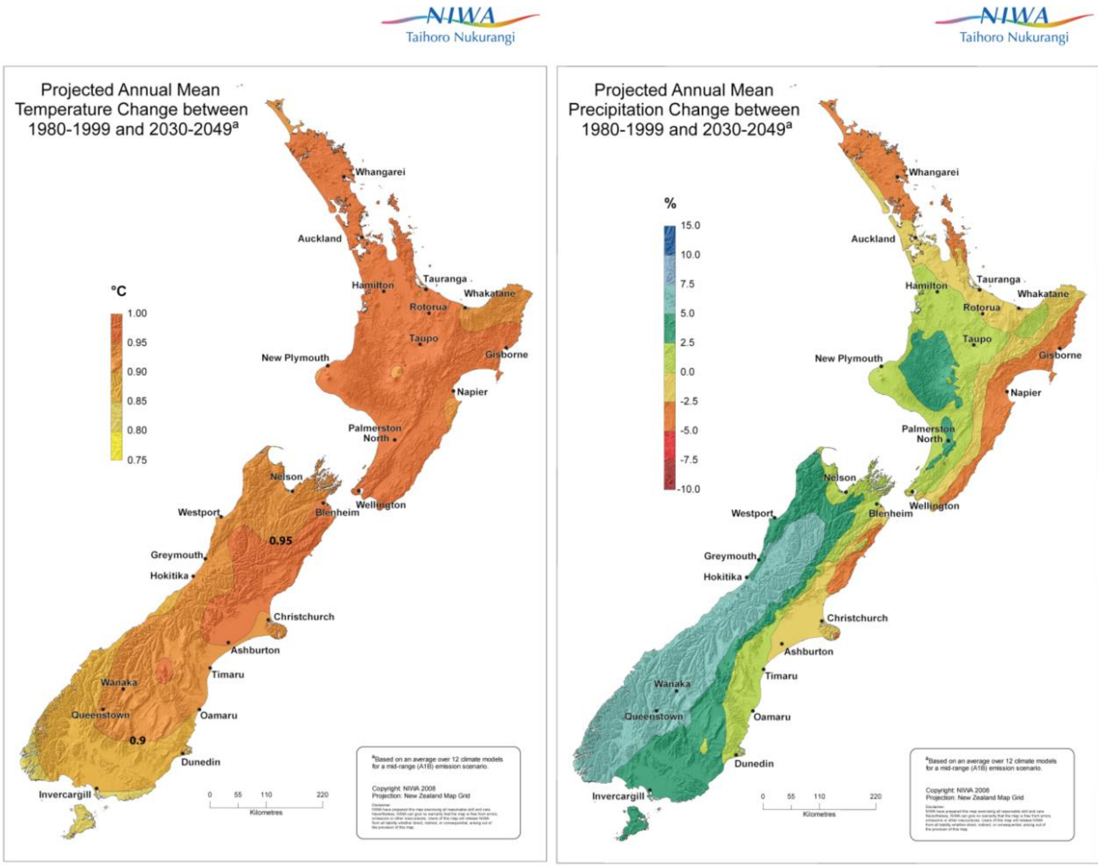

Figure 9: Projected 50-year changes in annual mean temperature (left, °C) and annual rainfall (right, %), for 2030-2049 relative to 1980-1999. Results are averaged over 12 climate models for the A1B emission scenario[38].

Major river flows are likely to undergo changes in seasonality as the winter snow pack decreases. Presently, flows in major South Island rivers are relatively low in winter and spring, since a large fraction of winter/spring precipitation goes into increasing the snowpack. In summer and autumn, snow melt contributes to relatively high flows. In future, increased rainfall (rather than snowfall) along the main divide in winter is likely to raise average river flows in winter and spring, while decreased snow melt is likely to reduce average river flows in summer and autumn. Hence, the seasonality of flows in the main rivers (those with headwaters near the main divide) is likely to decrease through the 21st century.

[38] *http://www.niwa.co.nz/our-science/climate/information-and-resources/clivar/scenarios*

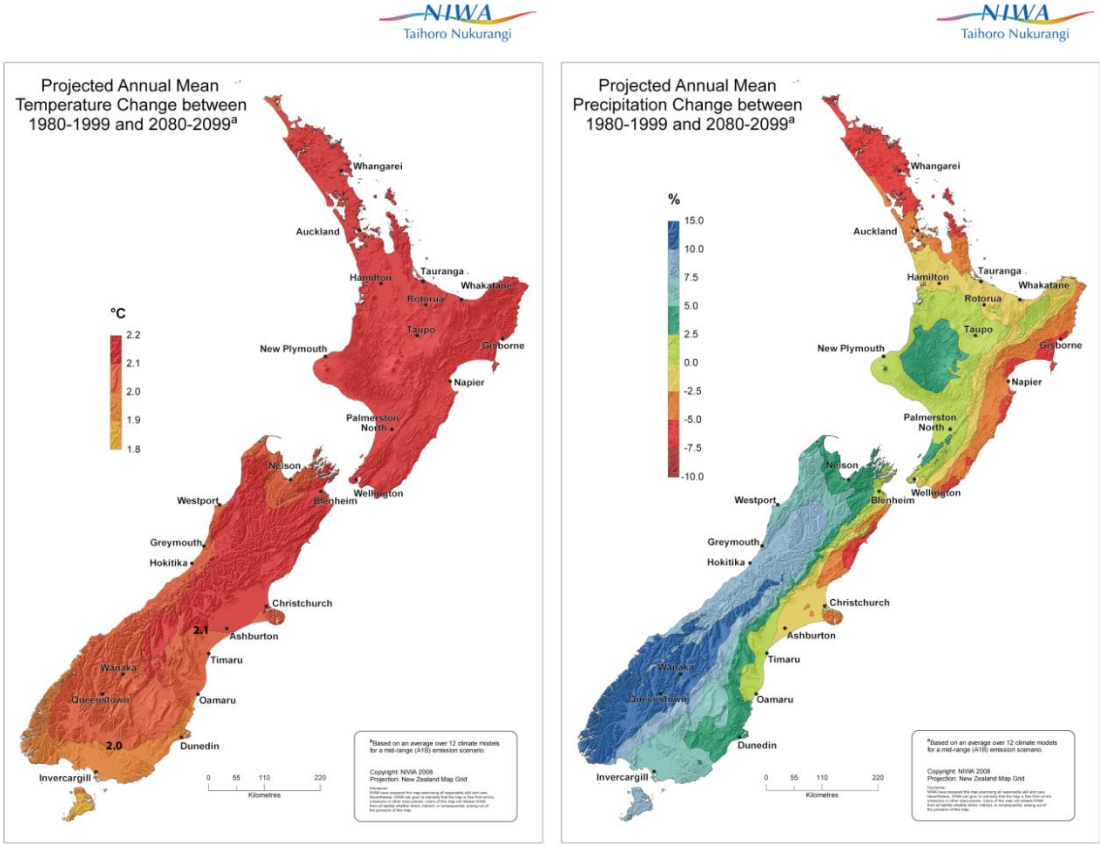

Figure 10: Projected 100-year changes in annual mean temperature (left, °C) and annual rainfall (right, %), for 2080-2099 relative to 1980-1999. Results are averaged over 12 climate models for the A1B emission scenario[39].

Hawke's Bay and the Makaroro River: average climate

In the Hawke's Bay Region, annual average climate changes are projected to be as listed in Table 2 (taken from Mullan et al. 2008). Projected temperature rises vary smoothly across regions and show little seasonal variation. The projected warming is associated with significant increases in average growing degree days (e.g. around a 50% increase, for a 10°C base temperature). Rainfall changes show a more localised nature and vary quite strongly with season. In Hawke's Bay Region, rainfall is projected to increase in summer and autumn and to decrease in winter and spring, but with an east-west gradient across the region, especially in the west where topographic influences are particularly important. This is associated with a projected increase in westerly winds across New Zealand in winter and spring, but a small decrease in summer and autumn.

[39] *http://www.niwa.co.nz/our-science/climate/information-and-resources/clivar/scenarios*

Table 2: Projected annual average 50- and 100-year changes (for 20-year means as indicated) compared to the 1980-99 mean in temperature and rainfall for Hawke's Bay Region. Temperature changes are given as averages across the Region while rainfall changes are given for Napier City, a representative location in the east of the region. Figures in brackets show the 90% confidence interval across the six main SRES scenarios. From Mullan et al. (2008).

Comparison Period	Change relative to 1980-1999	
	Temperature (°C)	Rainfall (%, Napier)
2030-2049	0.9 [0.2 to 2.3]	-3 [-14 to +14]
2080-2099	2.1 [0.6 to 5.4]	-4 [-20 to +11]

Projected rainfall changes for New Zealand are generally largest (in percentage terms) near the coasts and tend to be smaller inland (Figures 9 and 10, right panels). In the area of the Ruataniwha Water Storage Scheme, projected average rainfall changes are relatively small, with increases in summer and autumn and decreases in winter and spring. The headwaters of the Makaroro River in the Ruahine ranges are likely fed in part by 'spill-over' rainfall from the west, as is seen in many New Zealand rivers with headwaters near the main divide (Wratt et al. 1996). Hence during winter and spring, when the majority of the Hawke's Bay Region is likely to experience reduced rainfalls and increased drought risk (Clark et al. 2011), increased rainfall along the main divide is likely to boost average flows in the Makaroro River somewhat. Conversely during summer and autumn, flows in the Makaroro are likely to be somewhat reduced on average while rainfall across Hawke's Bay is likely to increase a by around five percent on average (Mullan et al. 2008). Note that such rainfall increases in summer and autumn will not necessarily lead to increased soil moisture, as evapotranspiration is also likely to increase with temperature.

Since the AR4, new climate model scenarios have been developed based on the RCP approach. Importantly for New Zealand, the latest suite of models takes better account of the expected recovery of the 'ozone hole' in the Antarctic stratosphere. Ozone recovery is expected to reduce future trends towards strengthened westerly winds in the Southern Hemisphere mid-latitudes (Arblaster et al. 2011). Such an effect may therefore reduce projected east-west rainfall gradients across New Zealand, although detailed scenarios for the New Zealand region have yet to be completed.

The average magnitudes of projected late-21st century rainfall changes (as a result of climate change) in Hawke's Bay and in the Ruahine ranges are comparable to those seen naturally from one year, or one decade, to the next as a result of the ENSO and IPO cycles. Moreover, the large spread of possible outcomes illustrated in Table 2 is in part a reflection of the uncertainties inherent in future climate projections. As discussed by Deser et al. (2012), the actual course of future regional climate will be a mix of the climate change signal and the effects of natural variability, and may not follow the average projected values. Hence, planning for and adapting to natural variations in the rainfall climate will be at least as important as responding to long-term climate changes, through to the mid-21st century. For the latter half of the 21st century (and beyond), some climate change effects, especially the increased drought risk across eastern regions, will likely stand out over natural variations in climate, even under the relatively conservative A1B scenario. For temperature, the effects of climate change are likely to have a significant effect on the risk of both heat waves (significantly more likely) and frosts (significantly less likely) by mid-century.

Hawke's Bay and the Makaroro River: extreme events

Rising average temperatures are almost certain to be associated with increased risk of hot days and heat waves, and with decreased risk of frosts and low temperature extremes (Mullan et al. 2008, Table 2.1; IPCC 2012). Changes in average rainfall (reductions in winter and spring, increases in summer and autumn) and increased evapotranspiration imply that the risk of drought, particularly in spring, is likely to increase significantly through the 21st century. Drought risk across Hawke's Bay is likely to at least double by the late-21st century and may increase by a factor of four or more, depending on the magnitude of climate change (Mullan et al. 2005, Clark et al. 2011). At the same time, the risk of heavy rainfalls, flooding and slips is also likely to increase by late 21st century, since a warmer atmosphere holds more moisture, leading to heavier rain when rain falls. A halving of the return interval (or a doubling of the risk) for heavy rainfall events is likely by the late 21st century, though the rate of change of risks around heavy rainfall events remain uncertain. In the shorter term, heavy rainfall and flood risk may not change significantly. Trends in the occurrence of heavy rainfalls across New Zealand over the past few decades have followed changes in average rainfall, with decreases in eastern regions and increases in the west (Griffiths 2007).

SUMMARY

New Zealand climate is variable and strongly regional, controlled by the strength and direction of the mid-latitude westerly wind circulation that blows across the country year-round. The major climate phenomena that affect New Zealand climate on an annual to decadal time scale are the ENSO (El Niño-Southern Oscillation) cycle, and the IPO (Interdecadal Pacific Oscillation). El Niño events (occurring more frequently during the positive IPO) are on average associated with stronger westerlies over New Zealand, higher than normal rainfalls in western regions and lower than normal rainfalls in the east and north. La Niña events (occurring more frequently during the negative IPO) are on average associated with weaker westerlies over New Zealand, lower than normal rainfalls in western and southern regions and higher than normal rainfalls in the east and north.

Global mean surface temperature, and the global energy balance, is controlled by the amount of solar energy absorbed by the earth and the amount of infrared energy radiated by the earth. In the past several decades, the only important change in the global energy balance has been the rapid increase in greenhouse gas concentrations in the atmosphere. In the twenty years since the first IPCC projections were published, global climate change has proceeded in a manner consistent with projections. A number of components of the climate system (e.g. sea level, Arctic sea ice extent) have been observed to change more rapidly than projected.

Climate change projections are based on a number of scenarios of global emissions of greenhouse gases and aerosols, which assume different futures in terms of demographics, economics and technology. The A1B scenario is often taken as representative of future changes, being in many ways in the mid-range in terms of future atmospheric greenhouse gas concentrations and global mean temperature changes. The A1B scenario remains plausible, since the pattern of change associated with A1B is very similar in form to that seen with other scenarios. However, in light of recent emissions, and recent analysis of future pathways, A1B may be conservative in terms of the magnitude of climate change by the end of the century.

Global mean surface temperature rise is likely to be at least 3°C by the end of the 21st century and is quite likely to reach 4°C or more. The target of no more than 2°C of warming, agreed to at the UNFCCC meeting in Copenhagen in 2009, is virtually certain to be exceeded. Warming (as already observed) is very likely to be greatest in high northern latitudes and least over the southern oceans. New Zealand is likely to warm somewhat more slowly than the global average. Projected rainfall changes through this century follow a broad pattern of wetter conditions near the equator and poleward of around 45° latitude, and drier conditions in the subtropics between around 25° and 40° latitude. For New Zealand, rainfall changes will be critically dependent on changes in the westerly wind circulation, which is expected to increase over the country during winter and spring, and decrease over summer and autumn.

New Zealand is likely to see relatively uniform temperature rises across the country, between 2° and 3°C in most areas by 2100 (a rate slower than the global mean warming rate). Rainfall changes are likely to exhibit an east-west gradient associated with the main mountain chains and changes in westerly wind strength. Winter and spring are likely to see increased rainfall (5-10% typically) in western regions by 2100, with similar-magnitude decreases in eastern and northern regions. However, summer and autumn are likely to experience increases in rainfall in eastern regions and decreases in the west and far south (magnitudes on the order of 5%). The magnitude of projected average changes is well within the range of natural variability, hence it must be borne in mind that the actual year-to-year (or decade-to-decade) sequence of change is unlikely to follow a simple linear trend.

Hawke's Bay is likely to see climate changes consistent with the picture above for the whole country. Warming of between 2° and 3°C is likely across the whole region by 2100. Rainfalls are likely to decrease in winter and spring, and increase slightly in summer and autumn. Flows from the headwaters of the Makaroro River are linked to rainfalls coming from western regions into the Ruahine ranges, hence flows from the headwaters of the Makaroro River are likely to exhibit small average increases in winter and spring and small decreases in summer and autumn.

Associated with changes in the average climate, the risks of various extremes are likely to change significantly by the end of the century. The risk of heat waves and drought conditions are likely to increase significantly, while the risk of frosts and cold nights are likely to decrease. The risk of heavy rainfall events is also likely to increase, although it is likely this will not become evident in Hawke's Bay until the late 21st century.

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