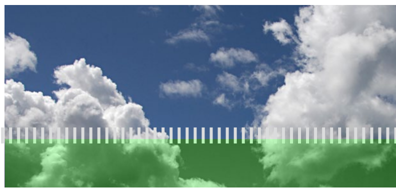
Chapter 2. Climate

The changing climatic environment for New Zealand's land-based sectors



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Abstract

Initially this chapter examines the scientific consensus around global climate change and identifies the main concepts and processes as a primer for land management professionals. It then moves onto the main focus, exploring evidence of change in the New Zealand region. Observational and process studies are examined as well as the latest sets of future projections. Some new insights are introduced including the recent attribution of New Zealand land temperature change to global climate change. The reader is provided with knowledge and information for understanding climate change and tracking its implications to his/her region and farm. New Primary Sector Adaptation Scenarios (PSAS) are introduced that are used in the following sector chapters to explore potential impacts and adaptations. As well as providing essential background, the chapter examines the latest science for the New Zealand region, highlighting evidence that the primary sectors are experiencing and will continue to face a changing climatic environment.

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1 Introduction

The impacts of global warming and regional climate variability provide a strong rationale for adapting New Zealand's primary sectors to climate change. In 2007 the Intergovernmental Panel on Climate Change (IPCC) published its Fourth Assessment Report (AR4), concluding warming of the climate system is unequivocal and that most of the observed increase in global average temperatures since the mid-20th century is very likely (> 90% chance) due to the observed increase in anthropogenic (human activity sourced) greenhouse gas (GHG) emissions (Meehl et al. 2007). This overarching conclusion is based on multiple lines of evidence drawn from a large body of published science. When this is examined in detail there is considerable depth in the underlying science, but it is also complex and specialised creating a significant challenge for public communication. This is part of the public discussion around the science of global climate change that has emerged as societies grapple with reducing GHG emissions.

While global-level climate change provides important context, it is really only a starting point for New Zealand's primary sector managers who are seeking to adapt to the direct effects of these shifts. The sectors need a different level of information to guide their adaptive responses, in particular knowledge of change in the regional climate system and exploration of the range of plausible future climate scenarios. Adaptive primary sector management also needs estimates of impacts guided by the scenarios across primary production planning timeframes, localities and production systems. This knowledge will support a better understanding of vulnerabilities, and robust decision making against the range of possible future climate outcomes.

This technical review brings together some fundamental climate science for primary sector adaptation in New Zealand, focussed on the perceived needs and interests of the land management professional. By introducing the 'core proposition' of climate change in an earth systems framework, the chapter provides some insights into global level changes to set the context. It then moves to the main focus, extending this systems approach to the regional level. It looks at sources of natural variability, evidenced from observational studies as well as emerging projections that allow scientists to develop plausible future scenarios for New Zealand's primary sector. It introduces some PSAS designed specifically for production system analysts to use for impact and adaptation assessment. The chapter concludes with a short discussion of how information from scenarios and climate science contribute to the ongoing process of adaptation in the primary sectors.

2 Global climate change

The core *proposition* of global climate change is that GHGs are being released by human activities over and above the capacity of the carbon cycle to sequester them, and, therefore, accumulating in the atmosphere. Given their physics and radiative properties, this mix of gases redirects energy towards the top of and across the atmosphere. This means that less energy is transferred back into space, leading to an energy imbalance (more coming in than going out). This extra energy heats the earth causing increased evaporation and raising the atmospheric concentration of water vapour (the most important GHG in terms of its short-term warming potential), thus adding to the energy imbalance. One net effect of this feedback process is a warming in the lower part of the atmosphere and at the earth's surface, so that energy going out at the top of the atmosphere will be in balance with solar inputs.

2.1 Scientific consensus

The grounding of this 'core proposition' in science is important because the implications of mitigating GHGs have large socio-economic consequences. Mitigation to reduce the GHGs released from human activities involves value-based decisions and trade-offs concerning ways that society can de-carbonise the global economy. Such economic and value-based decisions occur well outside climate science (Mastrandrea et al. 2010).

Because of this, as mitigation responses are formed and shaped, there is naturally intense public discussion on the science, and a range of texts, books and public communication activities provide commentary. This has led to a range of views being expressed about the core proposition – both in New Zealand and internationally –that are popular commentaries rather than mainstream climate science (examples relevant to New Zealand include Morgan & McCrystal 2009; Plimer 2009; and Wishart 2009 among others). The science itself is also changing, as aspects of the core proposition are re-evaluated, contested with evidence and progress made (Box 2.1).

Within this discussion, the climate science community continues to develop and communicate a strong consensus about the validity of the core proposition. A 'consensus' does not mean that every single detail of the science is agreed upon. Rather it illustrates that the majority of scientists think that the core proposition is, on balance, the most appropriate conclusion based on available evidence. For example Figure 2.1 displays one survey of the international research community: in this case 3156 practising climate scientists were asked their views on the validity of the greenhouse hypothesis (Doran & Zimmerman 2009). This illustrates that the conclusion about the core proposition is by far the dominant mainstream science view, with over 90 per cent of participants in this field in agreement. This is in contrast to much lower levels of agreement among the general public, where 56 per cent agree with the core proposition and 38 per cent do not.

Box 2.1. How global climate science is changing since the 2007 Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change.

The IPCC (2007) AR4 report provided an overview of global climate change science documenting where there was agreement and where more science was required at that time. It summarised available published scientific literature up to 2005–06.Since then, the science has continued to develop and a number of new perspectives have emerged since the AR4, for example:

- Some aspects of the climate system appear to be changing faster than earlier thought (Rignot et al. 2011; Spielhagen et al. 2011). New analysis techniques allow the robustness of the overall conclusion to be evaluated in light of key uncertainties (see Box 2.2). These studies show that the climate system is heading toward change despite uncertainties in factors like climate sensitivity (van Vuuren et al. 2011).
- Although there are still uncertainties, the processes of ice-sheet melt are now better-understood and there is potential for it to occur more rapidly than previously documented (Das et al. 2008). One revision of sea-level rise projections suggests that it was under-estimated in 2007 (Allison et al. 2009) but similar revisions of sea level rise estimates are ongoing.
- Observed droughts have a changed nature that can be linked to the combined effects of natural variability and anthropogenic warming (Baines 2009).
- New observation-based studies of climate sensitivity have confirmed the IPCC (2007) model-based estimate of ~3°C increase in mean global temperature for a doubling of carbon dioxide (CO_2) concentration. One study shows that when considering only 'fast feedbacks' such as water vapour the estimate is around ~3°C. However, when considering slow feedbacks (e.g., changes in ocean circulation and chemistry) it approaches ~6°C. Scientists are now considering the prospect of irreversible climate changes for 1000 years and more (Solomon et al. 2010).
- The World Meteorological Organisation identified the last decade (2000–2010) as the warmest on record[1].
- Global CO_2 emissions from fossil fuels in 2008 were 40% higher than those in 1990. Even if global emission rates are stabilised at pre-industrial levels, just 20 more years of global emissions would give a 25% probability that warming exceeds 2°C, even with zero emissions after 2030 (Meinshausen et al. 2011).
- Climate models continue to be improved. In particular, their ability to simulate ocean circulation and Sea Surface Temperature (SST) changes. Experimental modelling opens up the prospect of decadal-scale prediction (e.g., Smith et al. 2007; Keenlyside et al. 2008).

These are examples of the type of work that has emerged post 2006. The IPCC is currently in the process of formulating its Fifth Assessment Report (AR5) which will comprehensively update climate science, and is due to be published in 2013/14.

[1]http://www.wmo.int/pages/mediacentre/press_releases/pr_904_en.html (accessed 8 April 2012).

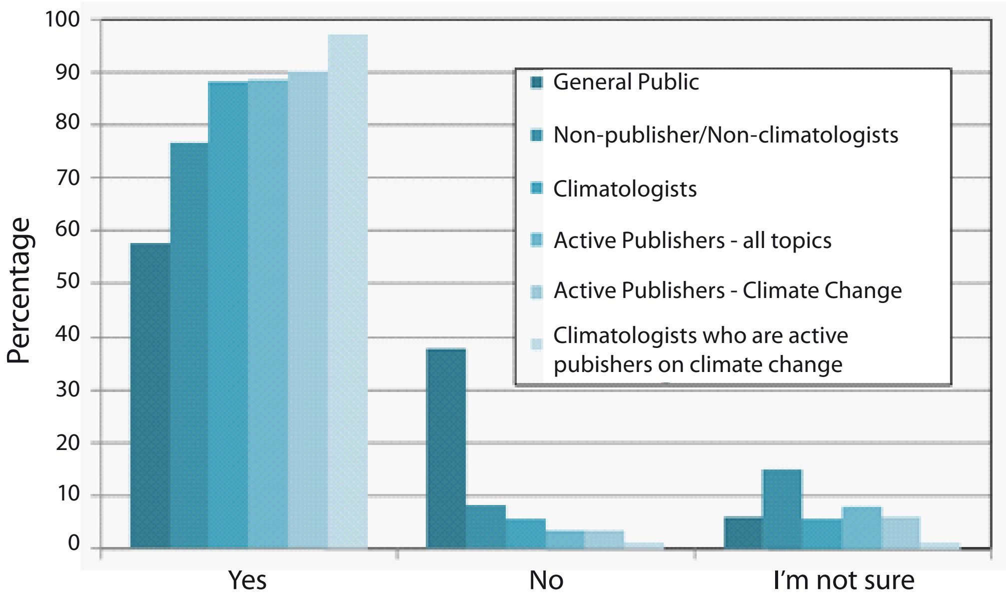

Figure 2.1. Surveyed response to the question, 'Do you think that anthropogenic global warming is occurring?' Reproduced with permission from Doran & Zimmerman (2009).

Opinion-based surveys of this kind have their limitations because they involve a degree of subjectivity and represent one point in time. Another way to gauge the mainstream consensus is to identify what leading scientific institutions have advised their governments and the communities about climate change. The IPCC, under the charter of the United Nations, has been the main organisation charged with this task and they have described the warming component of the core proposition as 'unequivocal,' with attribution of this warming to manmade GHGs 'very likely' (IPCC 2007). The process of developing this consensus was possibly the largest scientific collaboration ever undertaken (Fitzharris 2007), involving thousands of scientists, and included public and stakeholder consultation via the open and extensive review process.

However, the IPCC is not the only leading scientific organisation charged with this task. National academies of science have also been asked to form evidence-based judgements about the core proposition. Table 2.1 identifies four example synthesis reports published since 2007 from national level agencies, and details their conclusions about the core proposition. All four examples convey a high degree of certainty about human-driven global climate change, put together by independent scientists who advise their respective governments.

The summary statements formed by science institutions are naturally conservative – the very process of rigorous evaluation of scientific evidence through collaborative review means that the statements are designed to reflect where there is considerable depth of scientific knowledge. It takes some years to form these stated consensus views. More often, the most recent scientific work is not emphasised in these processes. For example, the IPCC needs to set a practical cut-off date for material it evaluates, which is well before the final release of their synthesis reports. As a result, there are alternative perspectives from individual and smaller groups of climate scientists who are actively working on climate change, who suggest that the IPCC and other institutions underemphasise the level of severity. The Copenhagen diagnosis (Allison et al. 2009) is an example of a smaller group of active climate scientists who chose to communicate a more high-risk view of climate change to decision makers.

The science consensus on global climate change is at an important juncture in this review for land management professionals focussing on adaptation. On the one hand this audience is primarily interested in the changes affecting production in the local region, and in-depth review of the science behind the consensus on climate change is not highly relevant.

Table 2.1. Recent synthesis reports and conclusions from various National Academies and institutions on the global climate change proposition as direct quotes from the executive summaries.

Variable	***Current conditions***
The Critical Decade Australian Climate Commissioner (Steffen 2011)	'The evidence is that the earth's surface is warming rapidly in now exceptionally strong, and beyond doubt.'
Climate Change: A summary of the evidence British Royal Society, (Royal Society 2010)	'There is strong evidence that changes in greenhouse gas concentrations due to human activity are the dominant cause of the global warming that has taken place over the last half century.'
Solving the Climate Dilemma German Advisory Council on Global Change (WBGU 2010)	'New research findings illustrate that the physical leeway for the protection of the Earth's climate has become very narrow.'
Global Climate Change Impacts in the United States United States Global Change Research Program (USGRS 2009)	'Observations show that warming of the climate is unequivocal. The global warming observed over the past 50 years is due primarily to human-induced emissions of heat-trapping gases.'

On the other hand, in order for land management professionals to move forward constructively on local and regional adaptation, they must develop a degree of trust in the science which also includes knowledge and confidence around global climate change (Stokes & Howden 2010). As trusted members of their communities they are often asked by their fellow professionals and land managers to help navigate through the public discussion on climate change. This body of science certainly becomes more relevant when considering GHG mitigation in the primary sectors.

There is insufficient scope in this review to provide the in-depth discussion of climate science required to properly trace the foundations of the consensus. This would require a highly detailed and lengthy treatment of the subject, which provides the reader with insights into the methodology, background concepts and quality of work. Readers who are interested in the science at this level are encouraged to consult Pittock (2005) for a science primer or Morgan & McCrystal (2009) for an analysis of the public discussion of global change science. However, it is important to briefly lay out some of the background to global climate change (Box 2.2) so that regional change can be discussed in a meaningful manner. The most important factor is that climate is viewed as a dynamic system.

Box 2.2. Global climate science foundation for the land management professional.

Global climate is a system of energy balance and exchange between three main components: atmosphere, ocean and land (*including* ice); and where the energy input comes from the sun. The main exchanges are shown in Figure 2.2. It is a system of 'forcing', 'responses' and 'feedbacks' between these components. These feedbacks occur over short and long timeframes at local to global level. Since the 19th century the process of radiative transfer within the earth system has developed from a theory based on key inferences from laboratory physics, to a well observed phenomenon that is the now a central principle of modern earth systems science.

A warming of the global climate system is unequivocal based on a large number of independent observations over the last century. The earth is well monitored and this statement has been robust to challenges about data quality or analytical techniques. An example of observations taken from satellite and instrumental sensors is shown in Figure 2.3, which highlights a 0.7°C to 1.0°C rise in average temperature over the preceding 100 years.

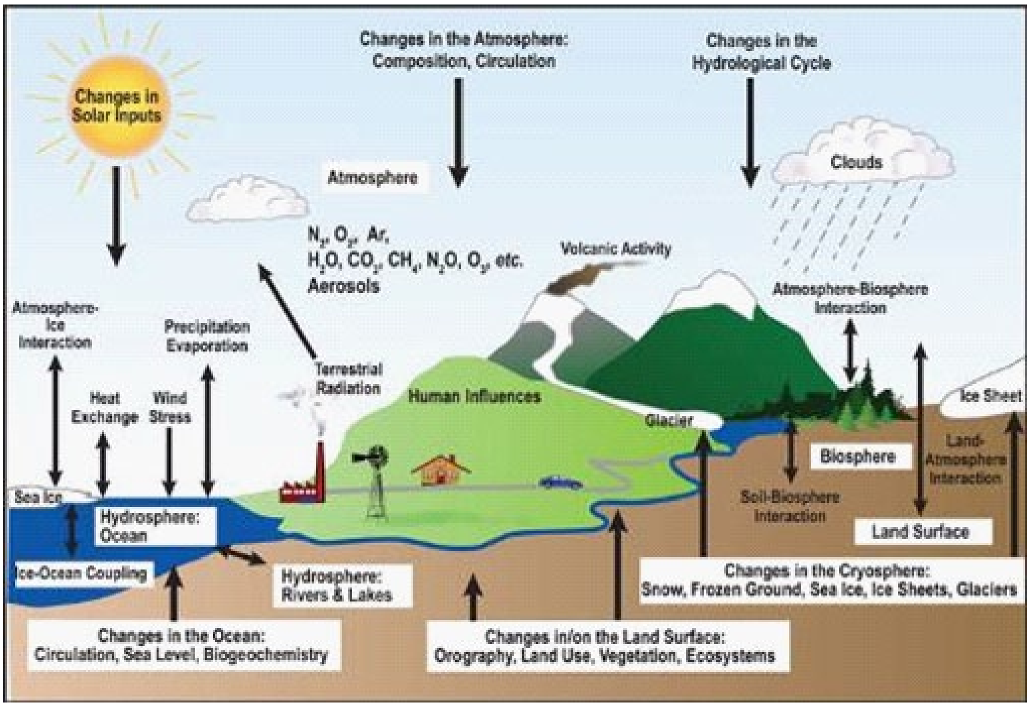

Figure 2.2. The global climate system showing the main land, ocean atmosphere interactions.

Figure 2.3 is an updated version of that, published by Hansen et al. (2010) and use the land-ocean temperature index which is a more complete indicator than land surface temperature alone. The challenge has been to deduce which part of the system changed to cause the observed warming (called 'attribution').

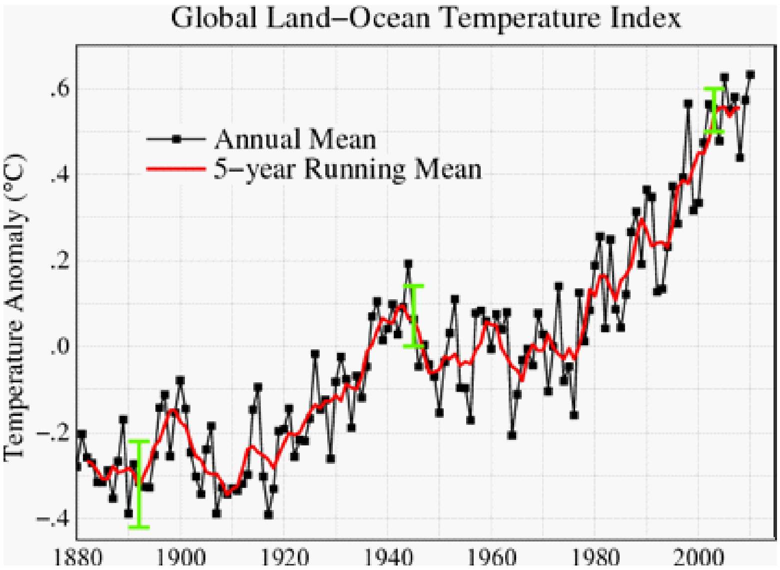

Figure 2.3. Global land-ocean temperature index (compared to 1980–1999 average) based on modern instrumental systems. Source: Hansen et al 2010. Bars denote the quartile range.

The greenhouse effect is containment of energy by the atmosphere, a result of the physics of some gases – mainly water vapour, with carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). A large bank of observational evidence (both with modern instruments and long-term climate reconstruction) shows that these gas concentrations have been rising this century and are at historically high levels given 600,000 or more years. This coincides with the observed temperature rise and remains the most likely factor driving the observed warming over the last century.

Solar forcing occurs because of variations in solar output, which influence the amount of energy at the top of the atmosphere. Through radiative forcing there are known effects on climate processes, which along with processes like the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), influence decadal variability in global temperature (Benestad 2010). Current observed change is not attributed to solar variability because recent warming does not correlate with observed changes in this forcing factor (Benestad & Schmidt 2009).

Variability and orbital change are well established as mechanisms by which global climate has varied over very long time frames due to slow variations in the Earth's tilt and orbit which control the waxing and waning of the ice ages on a 100,000-year time scale. GHG concentrations rise and fall with global temperatures, amplifying the cycles and greatly increasing their length. This is the well-studied Milankovitch cycle. The current observed warming is occurring at a much faster rate than this forcing process. Changes over the last 100 years have pushed greenhouse gas concentrations to a level not seen over the last 800,000 years.

Volcanic forcing involves small particulates transported high into the atmosphere from major volcanoes and causes temporary cooling over a 2–5 year period. For example, the eruption of mount Pinatubo in 1991 led to a reduction in global temperatures by around 0.5°C to 0.6°C, over a 2-3 year period. These events occur on a shorter timescale than greenhouse warming and do not explain the observed warming that has occurred over many decades.

System feedbacks account for the main on-going uncertainty in global climate science, and concern the indirect role, through the formation and behaviour of clouds, of the main GHG in the atmosphere – water vapour. While the thermal properties of water vapour are well understood, it is the role of clouds in the dynamic climate system and their influence on the global energy budget that is an active area of research. This leads to different estimates of future global temperature change. Estimates of 'climate sensitivity' range from 1°C to 6°C per doubling of GHG concentrations. The more likely figure of 3°C was identified by the IPCC, and this has been supported recently (Clement et al. 2009; Dessler 2010; Hansen & Sato 2011), but others suggest a lower estimate (Lindzen & Choi 2009, 2011; Loehle & Scafetta 2010).

Global climate models assist with interpretation and understanding of the causes of observed changes in climate. They make it possible to assess the relative contribution of the main driving components resulting in the increase in global temperature over the past 50 years or so. Many published experiments from modelling teams around the world identify GHGs as the explanative factor. This has also allowed certainty levels to be quantified around key aspects of climate change, for example the IPCC (IPCC 2007) states: '*Most of the observed increase in global average temperatures since the mid-20th Century is very likely due to the observed increase in greenhouse gas concentrations.* The term 'very likely' is calculated as a greater than 90 per cent chance of the statement being true.

Changes across continents and countries are likely to be non-uniform, based on current knowledge of future global warming, with the largest increases projected over the Arctic and the high-latitude continents of the Northern Hemisphere (Meehl et al. 2007). As the world warms, the tropical regions expand, leading to significant large-scale changes in climate patterns globally.

Changes beyond temperature will occur as temperatures respond to changes in radiative forcing, and other components of the climate system adjust, like shifts in circulation patterns which are thought to be the dominant source of precipitation change in New Zealand. With warming comes an expansion of the equatorial climate zone (a more tropically structured atmosphere), and there are also increases in average precipitation at the equator and the poles, and decreases in the subtropics and into the mid-latitudes. This warmer atmosphere can hold more water, intensifying or accelerating the hydrological cycle (Trenberth et al. 2003) with higher rainfall rates and longer dries. These hydrological responses are some of the more difficult to observe precisely and comprehensively.

Climate science continues to evolve, and the projected magnitude and scope of future climate change is always 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 and physical understanding of the climate system.

3 Change in the New Zealand region

While global level climate change science is important background knowledge, land management professionals dealing with adaptation are more interested in direct changes to the regional climate of New Zealand. In particular they would like reliable predictions of the water cycle with a high degree of confidence and certainty about:

- the next 3–6 months to guide their tactical decision making
- the next 3–10 years to guide re-investment decisions
- predictions for decades ahead to guide other a broad suite of adaptations
- sub-regions, individual farms and small landholdings.

Although there is strong knowledge about the climate system and there is a high level of confidence in forward estimates for some aspects of the New Zealand climate system, there are also a number of uncertainties that set limits as to what can be predicted with the high levels of precision and accuracy. Despite this, progress can be made by using science to provide objective estimates of current and future variability in the region.

3.1 New Zealand's climate system

To understand where there are capabilities and reasonable levels of certainty, as well as the limits of climate prediction, it is important to extend the system perspective from the global to the regional and local levels. Having a working understanding of scale is particularly important to guide interpretation of regional climate information (Box 2.3). This is because New Zealand has a complex maritime climate where a combination of latitude and topography dominate climate variability. Located in the Southwest Pacific the two main islands span the mid-latitudes (34° to 47° S). The major climate drivers are the band of mid-latitude westerly winds and the subtropical high pressure belt which move north and south with the seasons. 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 (Sturman & Tapper 2006). The rugged and mountainous terrain gives rise to considerable regional variability. There is also highly localised micro-climatic variability in some parts of the country, such as significant differences in 30-year average rainfall across a single pastoral holding. Despite this, there is a degree of 'certainty' in the New Zealand climate system in that there is a reliable source of water from the oceans that surround the Islands.

Box 2.3. Understanding scale in climate change and variability.

Scale is an important concept as it provides the perspective for measurement and analysis of climate. Much of the confusion about climate change comes from mis-understanding of scale i.e., which processes are dominant over what timeframes and which geographic range?

Climate processes are usually examined one scale, but there are also specific attempts made to link across scales. What happens at one scale does not necessarily translate directly to another, and there can be non-linear scaling relationships, particularly for rainfall. Having a sound understanding of scale is necessary for correct interpretation of climate information, which is particularly important when considering climate change impact and adaptation studies in New Zealand.

As shown in Figure 2.4, scale can be simplified into three relevant levels for the land management professional:

Macro scale. This includes the global processes described in Box 2.2. This is also known as 'earth system science', concerned with the way the globe responds as a whole to different pressures. This scale also encompasses 'large dynamics', such as the behaviour of ocean currents and their effects of continental climate. A good example is the El Niño Southern Oscillation (see Box 2.4) which is a macro scale process which links to climate at the meso scale. Global Circulation Models are used to study climate change represent processes at this scale.

Meso scale. The primary focus here is on regional level processes like the influence of large mountains on rainfall variability, the formation of synoptic systems and their movement across the country. The transect in Figure 2.5 and the whole-country maps in Figure 2.6 are an examples of climate examined at the meso scale.

Through regional climate models and other downscaling techniques the macro scale and meso scale are linked in climate change research. Just below this scale is the limit of the National Climate Observation Network, which supports mapping on a 0.05 ($5km^2$) grid.

Micro scale. The micro-climatic scale is around the area of a farm and its paddocks. Localised processes such as slope, aspect and sub-regional flows (example cold air drainage) dominate this scale. These are not measured systematically, only on a site-by-site or on a 'case study' basis. Processes at this scale are generally not included in current climate change modelling. Below this scale are micro meteorological processes, for example the ability of a crop or tree canopy to modify temperature in its immediate environment.

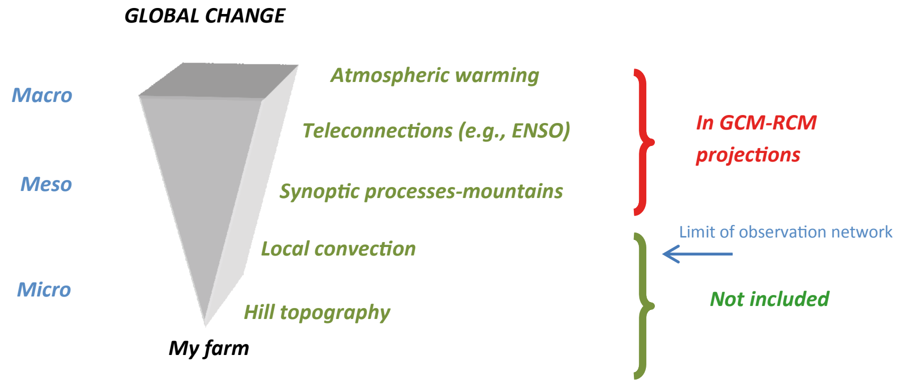

Figure 2.4. Conceptual diagram of spatial scales relevant for primary sector climate change impacts and adaptation.

There are also different temporal (time) scales which describe the period at which variability occurs. Hourly, daily and monthly scales are typically associated with agro-climatic analysis. There is also decadal and longer term variability. Global climate change occurs over a long period (30–50 year 'windows' at a minimum) and is mixed with other sources of variability that fluctuate at decadal and shorter timescales.

An instructive way to appreciate the full complexity of New Zealand's climate system is to consider a transect of the Southern Alps (Figure 2.5). As the predominant westerly flow interacts with the landscape it creates a complex mosaic of climatic zones. The most notable effect is the overall west-east gradient in rainfall, ranging from a median of 3 to 4 m per year in Westland to 12 m or more in the Alps, but less than 0.5 to 0.7 m in Otago and Canterbury (Wratt et al. 1996; Wratt et al. 2000; Figure 2.5). But there are also sub-regional (micro scale) effects, and some are not obvious in Figure 2.5, which form the environment for primary sector managers. Moving from west to east:

- A high rainfall belt characterises the coastal fringe with a calmer hinterland.
- This area then grades to high rainfall hill country, a result of uplift of the moisture and low level clouds that formed over the local ocean.
- The next zone is 'high country climate', where precipitation increases with altitude.
- Further east, there are regions of genuine alpine climate with permanent snow and ice cover.
- There are spill-over effects across the Alps where ice particles carried by high winds penetrating through the Alps, creating wet valleys on the lee side of the range.
- These wet valleys can penetrate the eastern plain at certain times, but this is predominantly drier in comparison to the west. This creates a zone of higher climate variability where irrigation is used to manage dry spells.
- The eastern coastal fringes are generally the driest environments in New Zealand.
- As the atmospheric moisture from the west falls out as rain over the mountains, heat is released into the air (when water vapour condenses). When the air descends east of the mountain range, it compresses and warms, creating characteristic warm 'norwesters' across the eastern plains. This latter component is known as the 'Foehn effect', after a similar process first observed over the European Alps.

The level of complexity depicted in Figure 2.5 is typical of much of the Southern Alps extending through the Central Alps of the North Island, although there are regions where not all of the processes operate or their strength is nullified due to topographic variation. There are also environments and events where this pattern does not hold:

- Although it is predominant not all the frontal systems have a westerly origin, and there are periods where frontal systems from other directions are persistent.
- Northland (the northern end of the North Island) is directly exposed to flows and storms emanating from the sub-tropics and there is little topographic modification. This region is also exposed to ex-tropical cyclone activity, particularly during summer, and these can also bring high intensity events as far south as the central North Island and upper South Island.
- Southland (the southern end of the South Island) is directly exposed to sub-Antarctic influences, with intermittent flow of cold moist air further to the north. These flows are also felt in the low to mid North Island.

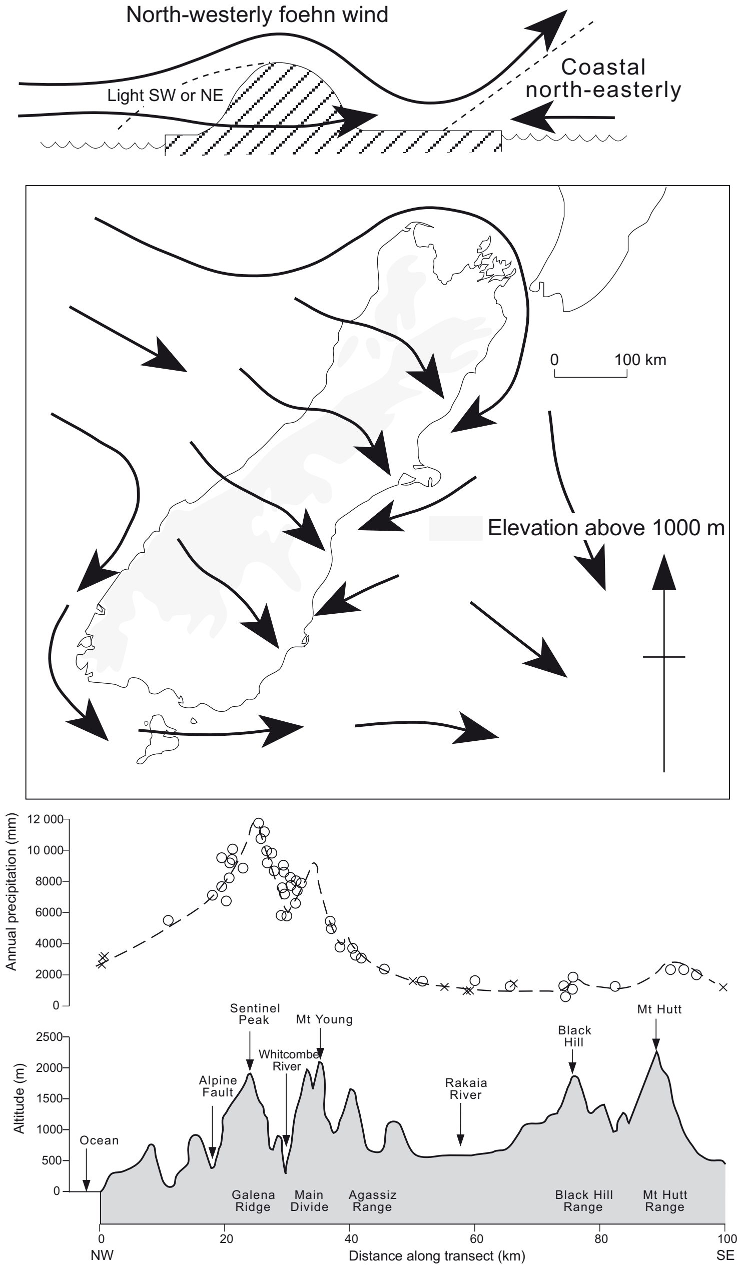

Figure 2.5. A 'complex maritime climate': the main flows influencing the South Island climate and associated rainfall transect (Sturman & Tapper 2006).

Much of the process complexity summarised in Figure 2.5 is also reflected in climate statistics. Mapping of climate variability has recently been updated in New Zealand using advanced techniques that include the topographic and other effects. These utilise available observations in the National Climate Network and provide a comprehensive 'virtual network' on a 5km-by-5km basis across the country (Tait et al. 2006; Tait & Liley 2009; Tait & Woods 2009;). The maps of average annual rainfall, temperature, radiation and evapotranspiration in Figure 2.6 are examples. These quantify the strong spatial gradients across New Zealand, where annual rainfall grades from more than 5m to as low as 0.5m in less than 100km.

There is also finer scale variability in the New Zealand climate system, namely at the local level which is the focus of primary sector management. Technically it is termed micro-climatic variability (Box 2.3), and where there is highly complex terrain it is beyond the ability of the mapping techniques used in Figure 2.6 to quantify, given the distribution of data in the national climate network. Factors like aspect, terrain shape and vegetation can influence climate variability at these scales. New Zealand's complex local landscape supports many unquantified micro-climatic niches, which local producers can exploit to their advantage (Powell et al. 2011).

- This complex regional climate system is coupled with global processes like anthropogenic warming and other 'large scale forcing patterns' as described in the section on 'variability' (See Box 2.4). Given the complex scaling relationships, there are a number of important things to consider when interpreting global climate change processes in New Zealand: Historical monitoring of New Zealand's climate has provided a crucial sample of Southern Hemisphere variability for the global network. However, any regional and local trends detected across the New Zealand land surface on their own have a very small effect on the overall global signal.

- There is a large and constant supply of moisture from the surrounding ocean and little rainfall is sourced from evaporation from the land surface. This will not change in a warmer global environment, but does make New Zealand vulnerable to changes in extremes (See Box 2.5). This contrasts to expansion of aridity and desertification and downstream climate process effects expected on continental land masses, under warming.

- The potential seasonal predictability of the New Zealand climate system is quite low, because of the large fraction of variability over the country arising from unpredictable ('random') processes. One analysis for rainfall suggests that, at best, 30 per cent of variability is theoretically predictable on the seasonal time scale (Madden et al. 1999), while 45–60 per cent of the seasonal variability in temperature has been identified as at least potentially predictable (Madden et al. 1999). More recently, Zheng et al. (2009) highlighted increased operational predictability using climate model ensembles as these improve into the future.

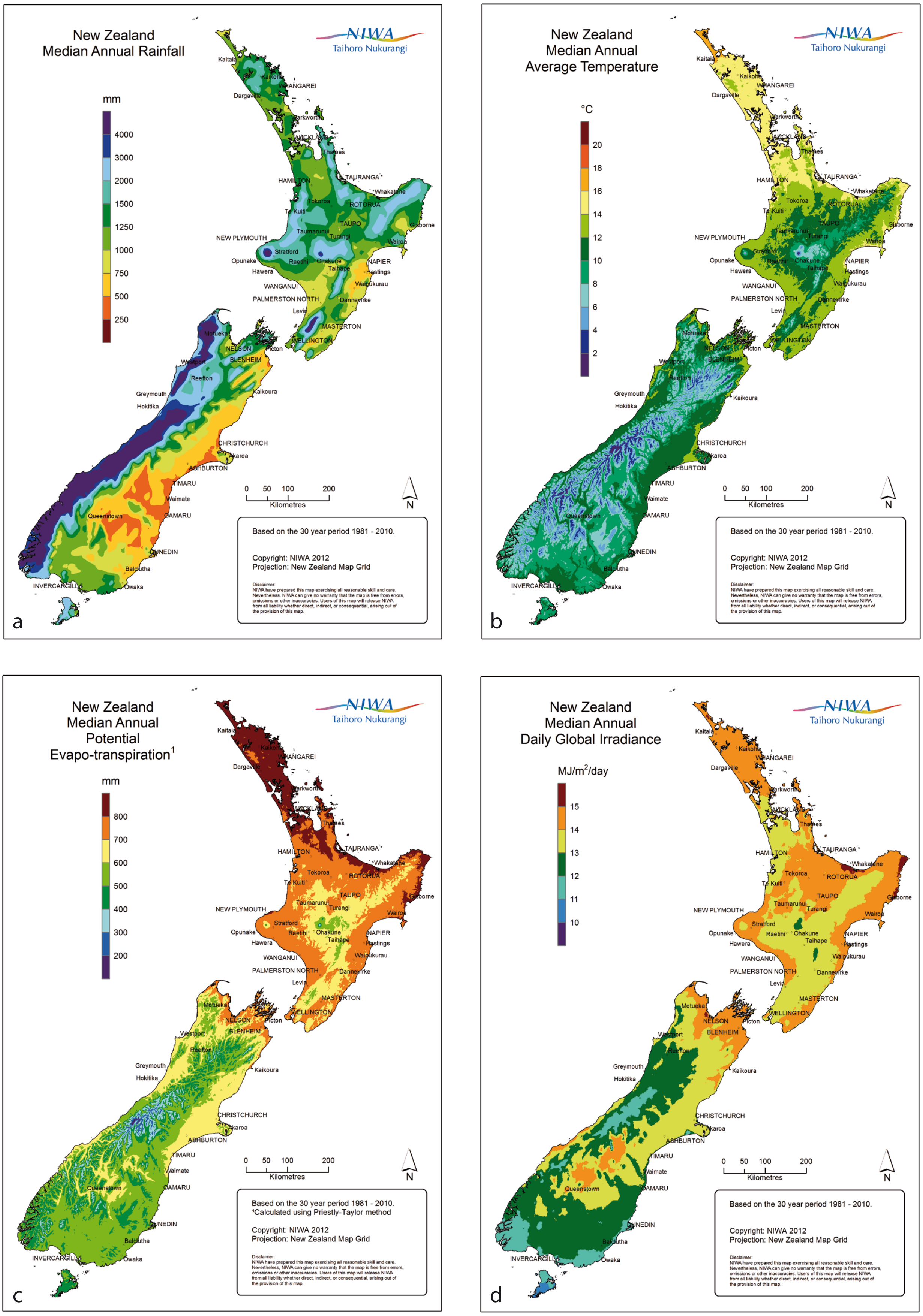

Figure 2.6. General climatology of New Zealand for the period 1981–2010 showing median annual values of variables. (a) Rainfall. (b) Temperature. (c) Evapotranspiration. (d) Radiation.

3.1.1 Sources of natural variability

One of the key advances in Southern Hemisphere climate science over recent decades has been improved knowledge of the dynamics and effects of large- scale teleconnections[2]. These large hemisphere and global scale phenomena have broad effects on the location, intensity, energy and moisture levels in the westerly flows and subtropical high pressure belt that drive New Zealand's climate. A brief description of the main larger scale climate processes affecting New Zealand is provided in Box 2.4.

These large scale processes lead to different modes of variability year-to-year and season-to-season. Collectively they form a part of what is described as 'natural variability'. For example, in a given year New Zealand's national average temperature may vary from long-term averages by a degree or more, with rainfall varying by around 20 per cent year-to-year. The pattern may be partly random, but there are also cyclical elements, such as seasonal variation in temperature, and semi-cyclical elements such as a varying return period of ENSO between 4-7 years. There are also known sources of decadal variability such as solar and major volcanic eruptions (Box 2.2).

Box 2.4. Sources of variability in the New Zealand climate system.

El Niño Southern Oscillation (ENSO)

- ENSO is a large perturbation to the global climate system, centred on the tropical pacific, which has detectable effects on temperature and precipitation around the Pacific and to some extent around the globe.
- ENSO has three phases, an El Niño where the Equatorial Pacific sea surface temperatures (SSTs) are warm, a La Niña where the SSTs are cool, and neutral phase. It is the main basis of seasonal climate prediction in New Zealand.
- Though there is some seasonal variation, during a La Niña New Zealand rainfall tends to be below normal in the south and southeast and above normal for the West Coast and north of the country. Temperatures tend to be warmer during a La Niña (Mullan 1995, 1996).
- During an El Niño, rainfall tends to be above normal in the south and west and below normal in the north and east of the country. Temperatures tend to be cooler during an El Niño.
- These overall average effects do not necessarily hold in every El Niño and La Niña event, given the influences of other processes.

Inter-decadal Pacific Oscillation (IPO)

- Scientists have found that there are subtle, decadal scale changes to ENSO variability, with 20 to 40 year periods of more persistent La Niña- or El Niño- type states.
- This phenomenon has a typical phase of around 20-30 years. During positive IPO phases, El Niño events become slightly more prevalent.
- There is a detectable IPO signal in New Zealand's precipitation, at least in some parts of the country (Folland et al. 2002).

Southern Annular Mode (SAM)

- This describes the natural variability in the Southern Hemisphere jet streams and associated bands of storms that usually lie over the southern oceans. SAM variations affect the underlying oceans and the energy exchanges between atmosphere and oceans.
- SAM is said to be 'positive' when the westerly winds over the southern oceans are stronger than normal, so mean sea-level pressures (MSLPs) are higher than normal over New Zealand.
- A 'negative' SAM is when the westerlies are weaker and shifted farther north towards New Zealand latitudes, while winds are lighter and pressures are higher than normal over higher latitudes.

[2]This means that weather at one location can be related to weather or patterns at another location. For example Auckland's relationship with Sea Surface Temperatures in the eastern Pacific Ocean.

- Recent analyses have shown that the SAM has a stronger influence than the ENSO on decadal trends in rainfall for many parts of the country, particularly the South Island (Ummenhofer et al. 2009).
- SAM is a climate process for which there has been an observed trend over the last three decades, consisting of a persistent and positive phase change over this time frame (Thompson et al. 2011). This is attributed to mix of anthropogenic greenhouse gases, but predominantly to ozone hole forcing. Given the recovery of the ozone hole, through worldwide reduction in use of chloroflurocarbons, there may be potential for this trend to reverse around mid-century (Arblaster & Meehl 2006).

Indian Ocean Diapole (IOD)

- Climate scientists have recently advanced knowledge of the role of the Indian Ocean in explaining regional climate variability. This has been partly the result of the Indian Ocean Climate Initiative, which has detected a inter-annual change in the energy mode of the ocean, called the Indian Ocean Diapole (IOD.)
- The effects of IOD on rainfall variability have been well quantified, with strong signatures in Western Australia as far as the midlands of Tasmania.
- Indian Ocean influences have been identified on New Zealand climate, which are used in seasonal forecasts (J. Renwick, pers. comm., 2012).

Local patterns

- Kidson (2000) identified 12 distinct synoptic weather types which characterise the dominant flow regimes over the New Zealand.
- Where the pressure gradients (and hence wind flows – the winds blow along the contours) which characterise New Zealand's climate variability are not simply a north-to-south or east-to-west flow. They may be far more complex, with subtle changes in direction. When considering the interactions with the landscape, these subtle features can have a large bearing on regional rainfall.
- The day-to-day transitions from one phase to another and their persistence are random, in that they follow no repeatable pattern, so their daily variability cannot be predicted a season ahead.
- Their relative frequency of occurrence is, however, strongly linked to the ENSO and the SAM and shows some seasonal predictability (Kidston et al. 2009).

It is critical for land management professionals not to confuse these sources of natural variability with the underlying signal of long-term change from global warming. A common mistake is to assume that because the year-to-year or inter decadal variation is large, that it somehow over rides the longer term change, and that this latter signal can be discounted. However, natural variability will always be superimposed on a long-term background of change and this collectively means the regional climate system moves into a new state. In this new state that combination of natural variability and long-term change provides the future extremes and variability for primary sector management.

3.2 Observed changes

It is common for land management professions to ask what observational evidence there is for climate change in the New Zealand region. Observed climate changes consistent with the global signals have been detected in the New Zealand region. However, in order to analyse and detect global scale climate change in New Zealand's climate, analyses must be undertaken to remove much of the known natural variability described above (Box 2.3). This might involve the use of trend analysis to isolate or tease apart the temporal variability in a time series, or the seasonal, annual and decadal variability. What is often not recognised is the need to have the same approach to spatial variability resulting from the micro and macro scale influences – so observations across large areas of land over a long period of time are needed to detect a global signal. There have been studies which examine trends in more localised areas, such as regional council districts (Baldi & Salinger 2008), which highlight this level of spatial variability.

Long-term temperature records can be built using observations for around 50–100 years in New Zealand, and various approaches to climatic reconstruction (e.g., palaeoclimate techniques) provide longer-term records going back several hundred years. Jones (1990) reported difficulties in constructing a reliable long-term series (500–1000 or more years) of temperature to investigate Southern Hemisphere changes, because of the relative lack of observational data in this region. However, by comparison, there are a number of long-term reconstructions of temperature for the Northern Hemisphere, which highlight recent warming as being a feature over the last 1000 years or more (Meehl et al. 2007).

3.2.1 Temperature

Looking at New Zealand's specific palaeoclimatic history, tree rings and other proxies have been successfully used to reconstruct a range of past climatic variables (Lorrey et al. 2011). These include:

- four temperature series (Norton et al. 1989; Palmer 1989: Palmer & Xiong 2004)
- one precipitation series (Norton 1987)
- one river flow series (Norton 1987).

The New Zealand reconstructions only extend back to the early 1700s because so few extractable and reliable tree-ring samples go back reliably any further in time, given the so called 'fading record' problem in New Zealand's palaeoclimate records. Palmer & Xiong (2004) highlight evidence of warming in New Zealand sites consistent with recent global trends, although it is neither statistically significant nor unprecedented in these records.

Advances in underlying data collection, management and analysis techniques are also improving the ability to track temperature change with the instrument record in our region. A good example is the Australian Climate Observations Reference Network – Surface Air Temperature (Figure 2.7, CSIRO & BoM 2012). It is the world's first continent-wide daily maxima and minima temperature series covering 100 years. Analysis of the new data set confirms trends found in previous analysis, that the Australian continent has warmed by approximately 1°C since 1910 and most of this warming has occurred since 1950. The warming trend is very similar to those found in international analysis, including those available for New Zealand.

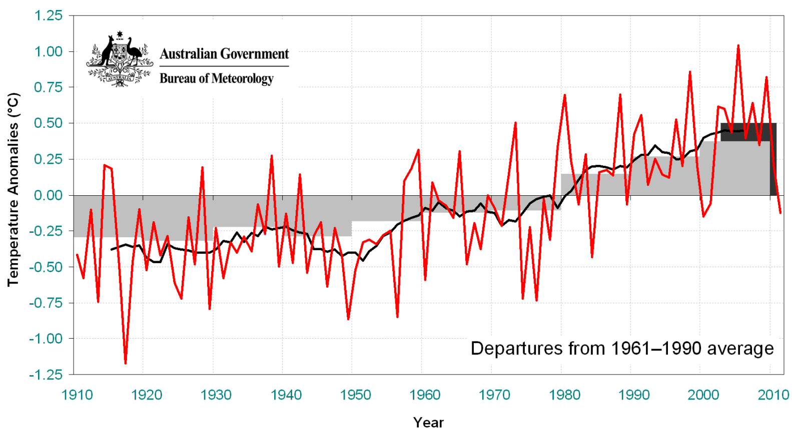

Figure 2.7. Annual (red line) and decadal (grey boxes) mean temperature anomalies for Australia (departures from the 1960–1990 average). The 11-year average (black line) and average for the most recent 10-year period (2002-2011, dark grey box) are also shown. Source CSIRO and BoM (2012).

In terms of New Zealand's instrumental record, the 'Seven-station' temperature series has been used for some time as one indicator of temperature change. This was first compiled in the late 1970s (Salinger 1980) but has undergone a number of methodological revisions and data updates since that time [3]. Seven representative sites were selected from around the country to provide a national aggregated series. This is the only instrumental data available allowing a temperature series to be extended back for more than a century, as there are few sites with valid instrumental records prior to the 1930s. Considerable work has been done to improve the quality of the data to account for site movements and other biases (technically called homogenisation), given the strong micro-climatic (e.g., altitude) effects.

[3]http://www.niwa.co.nz/climate/nz-temperature-record (accessed 8 April 2012).

Figure 2.8 presents the 'Seven-station' series showing the mean annual temperature trend, along with the trend an independently measured series of sea-surface temperatures (SSTs) in the New Zealand region. There is a significant rise in temperature over New Zealand consistent with the observed global warming (Box 2.2), around 0.9°C since 1909. There is also an eleven-station series which allows a similar national temperature aggregate to be constructed for a slightly shorter 80-year period, but sites were chosen so that no homogenisations were required. A similar increasing temperature trend is detected in this series.

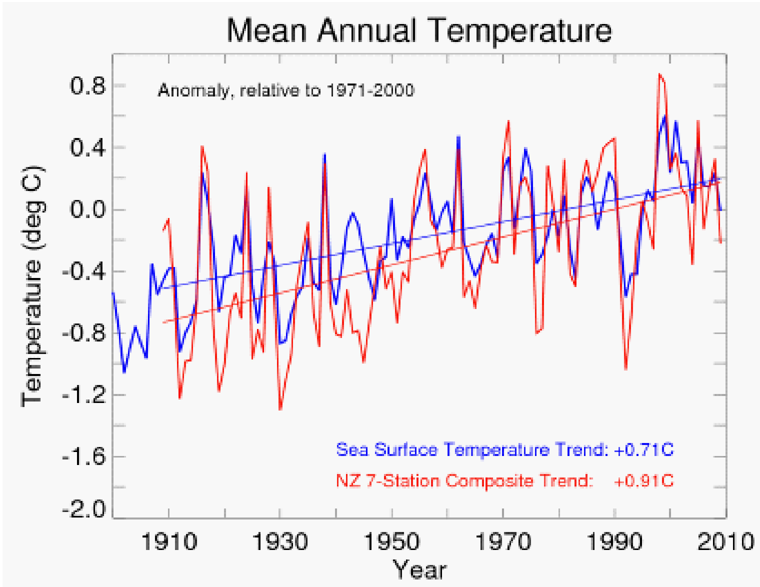

Figure 2.8. The Seven-station temperature and Sea Surface Temperature series for New Zealand. Source: http://www.niwa.co.nz/climate/nz-temperature-record (accessed 8 April 2012).

The Seven-station series is not the only study of its kind in New Zealand, and others have examined temperature trends with observations from other climate stations. The studies differ in terms of the length of record, sites used and techniques for quality control or analysis, so direct comparison is difficult. However:

- The observed SSTs from the New Zealand region are plotted alongside the observed temperature series in Figure 2.8. There is general agreement with the direction of the trend from the seven-station series, as well as much of the inter-annual variability experienced in the region. As discussed later (in Box 2.4 and Section 3.2) this is a highly important observation as it highlights the potential for process change in localised ocean-atmosphere heat exchanges that drive at least some of New Zealand's climate variability.
- Zheng et al. (1997) report a significant warming trend in average air temperature of 0.11°C per decade between 1896 and 1994.
- Salinger & Griffiths (2001) report significant increases in minimum temperature, reduction in numbers of cold nights and reduced numbers of frost days for the period 1951–1998, in a study that used data from 37 stations from 1930–75 and 51 stations from 1951–98. Both these studies were constrained to the national level, using a small number of sites across New Zealand where data quality can be assured.
- Using uncorrected site data, Withers et al. (2009) found a more complex regional picture, identifying around one-third of a national data set where temperatures were decreasing for the period 1900–1998 (mostly in the South Island). While Withers et al. (2009) used data from more sites, the time series were not tested for homogeneity or adjusted for site changes, making it difficult to draw robust conclusions from the study.
- Clark & Sturman (2009) investigated recent frost trends, constraining the data to the period 1971–2008 to ensure data quality and maximise the number of sites. As shown in Figure 2.9, they found increasing minimum temperatures and reduced frost risk when examining national aggregates built from 81 quality-controlled sites. However, regional differences in both the sign and strength of minimum temperature and frost trends were also evident.

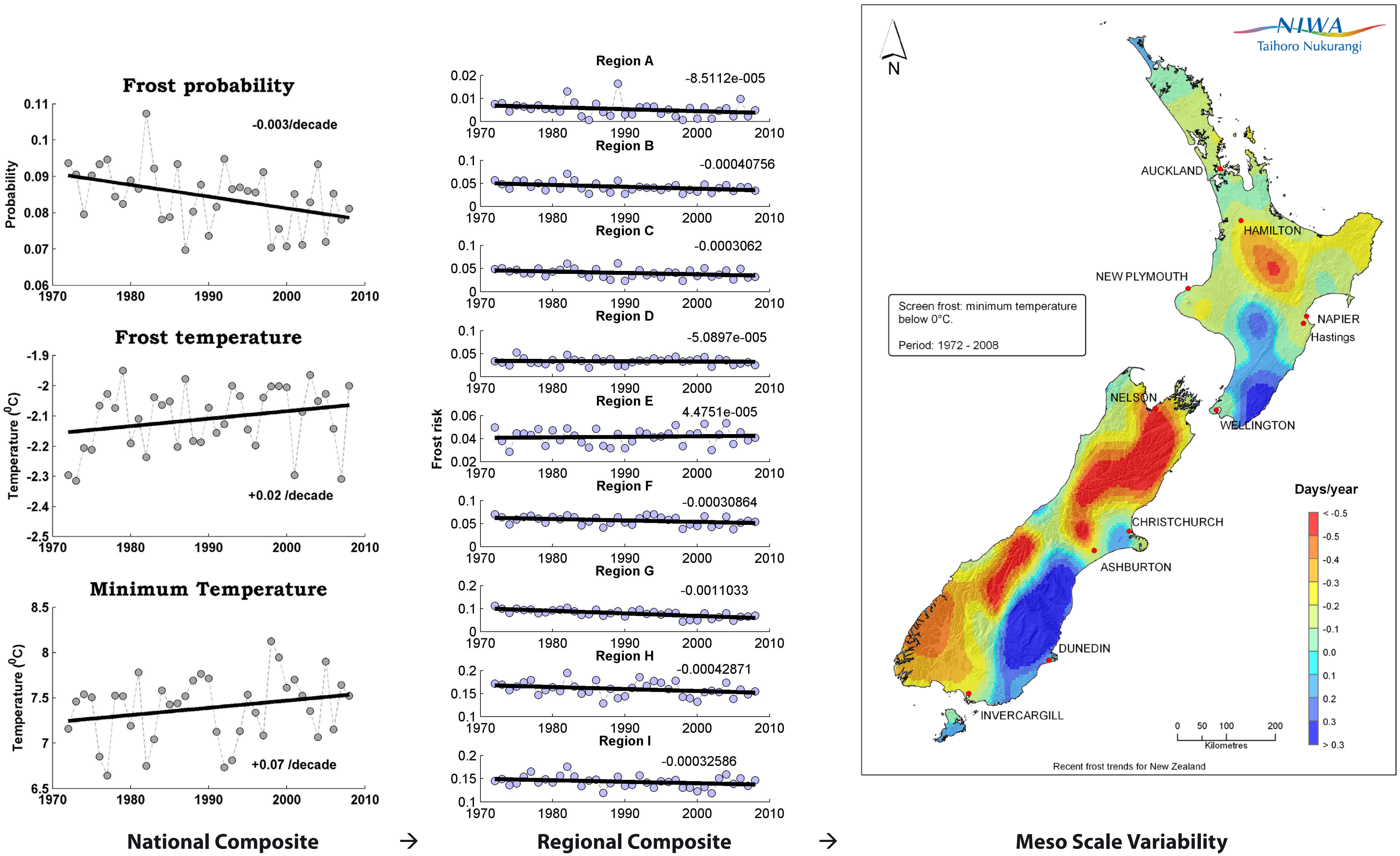

Figure 2.9. Trends in minimum temperatures and frost temperatures for a national composite of 81 sites, regional composites (A-I) of frost temperatures, and an interpolated surface of spatial variability in frost frequency trends. Regions A-I are New Zealand Meteorological Zones. Linear trend coefficients (units/decade) shown on figures. Adapted from Clark & Sturman (2009).

Figure 2.9 is an example of an effect found in most studies of surface air temperature change in New Zealand, namely the breakdown of trends found in global and national temperature aggregates (macro to meso scale) when examined at the local level (meso to micro scale). Individual site results are sometimes incorrectly used to question the validity of the global climate change process and its influence on the region (for example Withers et al. 2009). However, it is an important factor for primary sector adaptation as it illustrates the way the local climate system interacts with global processes. There are non-linear scaling relationships which must be considered, and the fact that regional trends can, in some cases, run counter to the global signal is a normal aspect of the countries complex maritime climate.

3.2.1.1 Temperature change attribution

Another commonly asked question concerns what changes may be driving observed trends once they have been detected. This is known as the scientific process of 'attribution' and involves sophisticated multivariate analysis and process modelling. It is a more substantive research task than trend detection alone. Extensive attribution work has been undertaken for global temperatures, but there has been a paucity of sub-continental and regional scale studies (Stott et al. 2010). This is starting to change, for example Karoly & Braganza (2005) highlighted the observation that Australian temperature trends are very unlikely to be caused by natural variability alone, and they are highly likely to be driven by forcing from GHGs released by human activity.

Recently, Dean & Stott (2009) undertook the first detailed attribution study for New Zealand's national temperature trend. Their study provided some new and important insights, concluding that:

- New Zealand surface air temperature and local circulation processes are highly correlated.
- There have been detectable long-term changes in local circulation, with an increase in the southerly flow across New Zealand since about the 1960s. This has kept the observed temperature increase lower than it would have been, essentially dampening the influence of global warming in the New Zealand region.
- This trend in southerly flow remains unexplained because climate models do not adequately simulate the process[4]. If the shift is part of decadal variability New Zealand could experience a period in the future where warming exceeds that being experienced globally.
- The 50-year trends in New Zealand temperature cannot be explained by natural variability alone, and are consistent with the processes of anthropogenic global warming. This conclusion is based on analyses using more detailed modelling, and careful analysis to remove biases and take the local processes into account.

3.2.2 Rainfall

For primary production, rainfall is probably the more important driver, as there are limits (both too much or nor enough water) where plants cease to grow or experience harm. When other climatic factors are not limiting, precipitation levels within these limits can have a direct proportional relationship to productivity.

For a number of reasons measuring, analysing and predicting rainfall is a more difficult task than for temperature. This is because the processes that yield rainfall events usually operate on small spatial scales and are very intermittent in time. Changes to important features of rainfall characteristics and process are not tracked over the long term. This is largely due to measurement limitations. For example to understand changes to rainfall intensity, features like the source of moisture and storm density should be examined. It is not possible to measure these features over the long term, either because they are resource intensive, the instruments have inadequate levels of precision or the processes themselves are impossible to quantify with current instrument technologies (Trenberth et al. 2009).

Despite these difficulties, climate monitoring since the 1950s has been sufficient to support some analyses of precipitation change In New Zealand. One recent study (Ummenhofer et al. 2009) examined precipitation across the last 30 years using the spatially interpolated daily rainfall data described previously (Section 3.1). There is evidence of strong, yet regionally and seasonally diverse trends in New Zealand's precipitation (Figure 2.10). It is worthwhile studying these in some detail, as the results indicate that quite dramatic changes are possible for the regional climate system in the future, given the strength of trends found in past observations confined to the

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[4]In climate model simulations there are biases in ocean circulation and subsequently Sea Surface Temperatures in the Antarctic and New Zealand region (Hoerling et al. 2010). This is due in combination to paucity of measurement and subsequently process representation in the models.

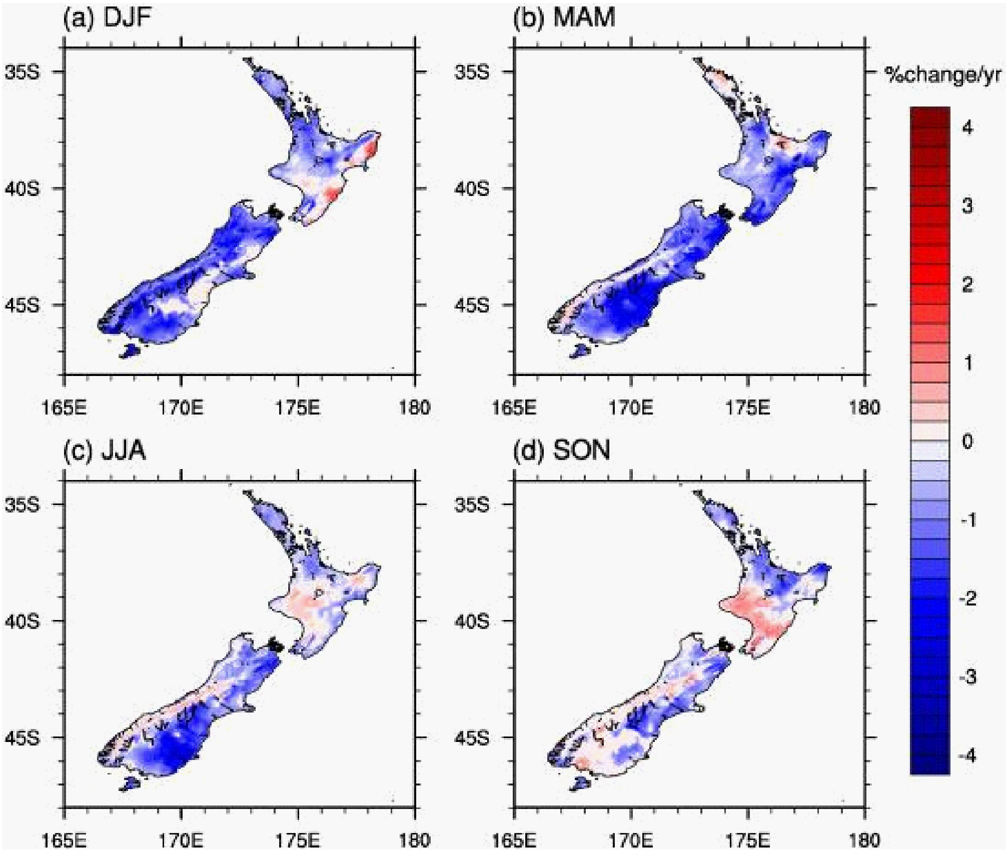

Figure 2.10. Trends in daily precipitation amount (percentage of long-term average per year) for New Zealand for the period 1970–2007. (a) Summer. (b) Autumn. (c) Winter. (d) Spring.

recent period of warming. The range of change found was large, up to four per cent increases or decreases per year over a 30-year timeframe in some regions. There is a complex regional pattern of increase, decrease and stability depending upon season and location.

Ummenhoffer & England's (2009) study went beyond trend detection and used a newly developed approach to multivariate analysis in order to attribute trends to different processes. As would be expected, trends in precipitation are a mix of complex interacting signals, some of which may be traced back to the global warming process, and others to natural variability (Box 2.4) - and each region has its own unique combination of natural and global drivers. For simplicity Ummenhoffer & England (2009) broke the country down into two simple 'change regimes', based on the dominance of different processes, where:

- **Northern regions** are dominated by local air-sea heat fluxes with some evidence of a secondary factor, and circulation changes are regulated by the tropical ENSO.
- **Southern regions** are dominated by larger general atmospheric circulations especially the changes in Southerly flow (as described by Dean & Stott 2009 as well as by Salinger et al. 2001). This also includes the subpolar westerlies modulated by the Antarctic Oscillation (Southern Annular Mode) and its strong shift towards a more positive phase.

Primary sector managers are highly interested in diagnosing the drivers of seasonal and inter-annual rainfall variability for their local region and property (micro-climatic scale). However, detailed attribution studies at this level have not been undertaken and are difficult – for example attributions of the recent run of drought events in the Waikato and the Wairarapa have not been undertaken, and it is not possible to provide guidance to local landholders around the extent to which this is a longer term change or natural variability. Given that the answer is always going to be some combination of processes, and the difficulty and expense required for local attribution studies, their worth is questionable, except in specific circumstances when there is a concentration of high-value, high-risk enterprises (see for example Powel et al. 2011). Although Ummenhoffer & England (2009) were able to describe two general change regimes at the broader level, and a changing overall southerly flow has been detected (Dean & Stott 2009), there is considerably more rainfall complexity at the scale of primary sector management.

3.2.3 Precipitation extremes

There are well founded physical relationships between temperature and rainfall extremes (the technical details are outlined in Box 2.5). Although complex interactions between the physics of this relationship and climate processes occur, the net result is an expectation that there will be an increase in the intensity of extreme precipitation events in future, in line with temperature changes. The presence of a long-term warming trend in SST observations in the New Zealand region (Figure 2.7) is an important observation in this context, as it highlights that the precursor conditions for this type of precipitation change are building in the New Zealand region.

Validly detecting and attributing long-term changes in precipitation extremes is problematic. A significant international observation study confirmed expected shifts in precipitation extremes over Europe (Lenderink & van Meijgaard 2010). The study utilised sub-daily data from one of the only geographically extensive and long-term networks of precipitation intensity monitoring. This study also found that a large (sub continental or macro scale) observation network of sub-daily monitoring over many years may be needed to provide an appropriate sample for detecting changes in precipitation extremes.

The implication of this work is that detecting precipitation extremes with any level of statistical confidence will be highly problematic in the New Zealand context. This is because of the limited geographic and temporal coverage of the network that monitors rainfall intensity. In addition, given the statistical basis for validly detecting long-term trends in extremes described by Lenderink & van Meijgaard (2010), the New Zealand land mass may simply be too small for valid analysis of long-term change to rainfall extremes.

The available observational studies confirm these difficulties. For example, Griffiths (2007) found evidence of both large increases and decreases in precipitation extremes across the county when analysing the available high-quality daily data (Figure 2.11). This re-emphasises that regional New Zealand has experienced differences in both the strength and direction of trends in the previous observed climate period.

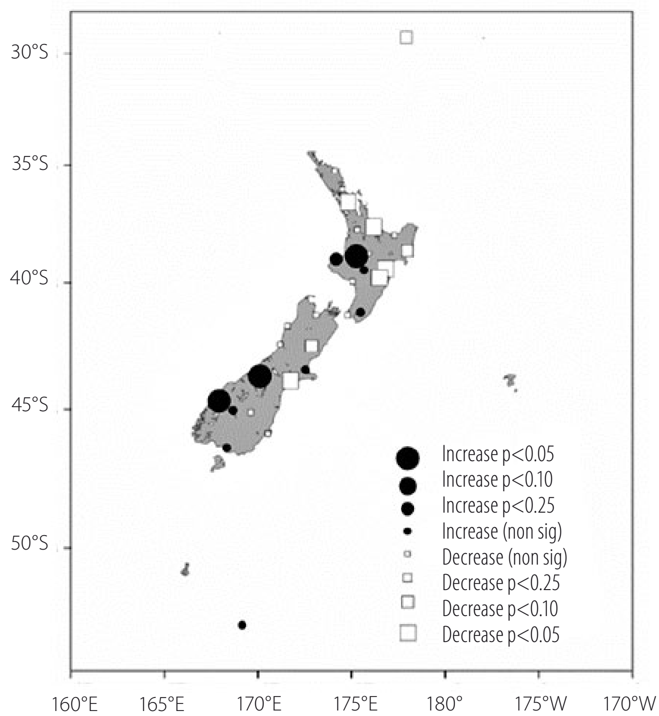

Figure 2.11. Trends in rainfall extremes (≥ 95th percentile for daily events). From Griffiths (2007).

More recently, Dravitzki & McGregor (2011) investigated the relationship between Waikato precipitation and large-scale climate variations, focussed on the period 1900–2007. They found that heavy precipitation in the Waikato is associated with the local air-sea fluxes described generally by Ummenhofer & England (2009) – more specifically, with periods of increased instability that produce a rapid sequence of mid-latitude cyclones or the presence of a blocking high to the east of New Zealand. Using a regionally representative time series it was found that there have been no significant variations in the total annual precipitation or in the occurrence or magnitude of extreme precipitation events since 1900. At the scale at which this study was undertaken local processes seemed to dominate, and although more investigation is required to test the robustness of the result, even large-scale teleconnections that have well established influences on national scale variability in New Zealand were not correlated with this locally representative time series.

Box 2.5. Effects of warming on climate extremes – key science for understanding impacts.

- The water-holding capacity of the atmosphere increases with temperature, as modified by relative humidity (Trenberth et al. 2003; O'Gorman & Schneider 2009). This is known as the Clausius-Clapeyron relationship, which quantifies the non-linear (exponential) relationship between temperature and humidity. Given this well founded physical law, the open atmosphere can hold more moisture as the general environment warms. This relationship changes the way rainfall is generated and falls, with a shift towards higher rainfall volumes when events do occur, with longer periods of no rainfall.
- In the New Zealand climate system this is an important process and key to guidance around potential future changes to extremes events, or intensification of the hydrological cycle (Pall et al. 2007; Sansom & Renwick 2007). For example, given high correlation with warming Sea Surface Temperatures (SST) more intense storms can be expected under warming (Emanuel 2005). This principal also scales to local air-sea heat exchanges in the Tasman, the source of rainfall across most of New Zealand.
- In New Zealand, general guidance is to plan for an 8 per cent increase in the intensity of extreme rainfall per degree of warming (Mullan et al. 2008 citing Pall et al. 2007). Land management professionals can access the High Intensity Rainfall Design System (HIRDS) (Thompson 2010) freely and perform calculations at any location in New Zealand[5].
- Recent advances confirm hydrological intensification is influenced by anthropogenic warming, particularly over large land areas, using both observations and models. The strongest evidence is from the Northern Hemisphere, which has widespread measurement networks for sub-daily precipitation observations going back over half a century (Lenderink & van Meijgaard 2010).
- Detection of change was only possible when considering larger land areas (sub-continental scales). Change was not detected in smaller land areas (around the size of New Zealand or smaller), where local processes dominate (Lenderink & van Meijgaard 2010).
- There are complex short-term feedbacks on synoptic patterns and local processes which are not yet fully understood, and the relationship depicted by the Clausius-Clapeyron equation may be too simplistic (Pall et al. 2009):
  - For example, it is important to estimate temperature effects on upward wind velocity to estimate storm track trajectories (O'Gorman & Schneider 2009).
  - There are complex relationships between intense storms, their tracking and frequency and surface -ocean warming (Trenberth 2005).
  - Links between extremes and processes like SAM and ENSO are also yet to be comprehensively investigated in the New Zealand context.
  - This provides a rationale to pursue process-based modelling of the regional climate system to improve the quality of regional projections of extremes (see Section 4.3.2) and improve the basis for change attribution studies.

[5] http://hirds.niwa.co.nz/ (accessed 8 April 2012).

4 Regional scenarios of climate change

Data from the climate models that are used to understand the processes and responses of the dynamic climate system can be analysed to provide statistical summaries of future climate. This provides a way to integrate much of the process complexity described in Section 3, and present changes in a more targeted form for decision makers, providing what has been termed 'climate change scenarios'. Model-based climate scenarios are not concrete 'deterministic predictions' of the future or 'forecasts'. This is due to a number of factors, including:

- a random component of variability in the global and regional climate system – including non-linear feedbacks
- model uncertainties like structural limitations (e.g., resolution and inability to represent some processes adequately)
- lack of physical and theoretical knowledge around some key processes
- the range of possible future greenhouse gas emissions.

Model-based scenarios are 'probabilistic projections' of a range of potential outcomes. Climate scientists are often criticised for making this type of distinction, particularly by decision makers who seek more concrete forecasts that would support a more prescriptive 'optimal' approach to decisions (Dessai et al. 2009, Chapter 2). However, it is an important distinction, which leads to discussion around the role of model-based projections in further impact analyses and the decision-making process (Section 5.1).

Contemporary global level projections of the earth's temperature are derived from free-running coupled Atmosphere Ocean General Circulation Models (AOGCMs) that are set up to simulate climate over 100 years or more. The contemporary models used to derive scenarios couple coarse resolution, physically based models of surface-ocean and atmospheric circulation (hence 'coupled'). The Coupled Model Intercomparison Project (CMIP; WCRP 2011) is a global initiative where output from a number (ensemble) of models run by climate research institutes is managed. It establishes a consistent experimental design to explore various emissions scenarios and their effects on the global climate system. All of these data are freely available to registered users[6].

The AOGCMs in CMIP are broad in resolution and do not include many of the complex processes that create variability across New Zealand (Section 3). Due to the relatively small scale of these processes, it is essential to downscale the AOGCMs to develop plausible future climate scenarios for this country. This contrasts with large continental land masses, where to some degree it is possible to develop plausible scenarios directly from analysis of the broader circulations that are simulated by AOGCMs.

4.1 Emissions scenarios

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 (Nakićenović & Swart 2000). The SRES scenarios are based on a set of possible socio-economic and technological futures, broken into two broad families (Figure 2.12). They do not include estimates of changes as a result of specific polices that reduce emissions. The 'A' scenario family is more focussed on economic and market considerations, while the 'B' scenarios are more focussed 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 co-operation.

Within A1, three main scenario types have been used: A1'B' for balanced (between clean technology and use of fossil fuels); A1'T' for a non-fossil and more green-technology future; and A1'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.

At the time of writing the global climate research community is actively working within the framework of a new approach to emissions scenarios, Representative Concentration Pathways (RCPs). These new scenarios are designed to replace the SRES scenarios, providing a more integrated basis for climate impact and mitigation research globally.

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[6]http://cmip-pcmdi.llnl.gov/ (accessed 8 April 2012).

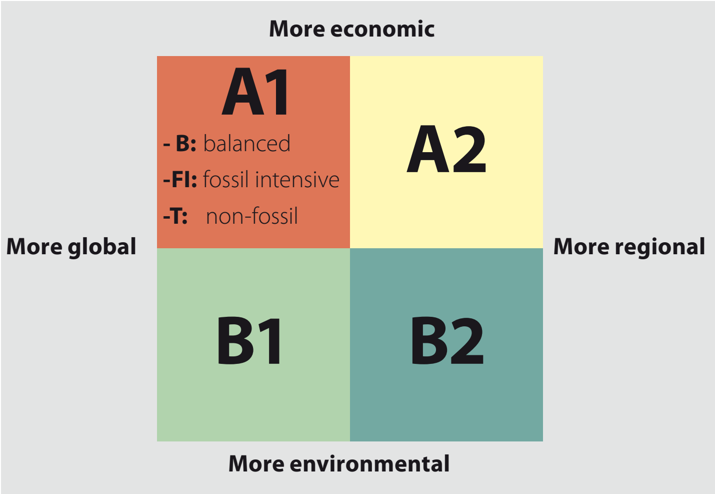

Figure 2.12. Schematic of the different families of IPCC SRES emissions scenarios. (Figure based on Nakićenović & Swart 2000).

There are four individual RCPs, which together span the range of radiative forcing values out to 2100 found in the open literature, i.e., 2.6, 4.5, 6.0, and 8.5 W/m^2. The RCPs are also supplemented to produce Extended Concentration Pathways out to 2300. For the purposes of the future scenarios considered in this study, which are based on the SRES family, it is worthwhile noting that:

- RCPs 4.5 to 8.5 approximately span the SRES range B1 to A1FI.
- By 2100, RCP 8.5 is roughly equivalent (in terms of global temperature increase) to A1FI, RCP6 to A1B, RCP4.5 to B1, and the lowest RCP is below the SRES scenario range.

4.2 National projections

Mullan et al. (2001) describe a downscaling scheme for New Zealand which utilises sea level pressure indices to downscale AOGCMs. The approach has been used for both the IPCC Third Assessment Report (TAR) and AR4 global climate models. Evaluation of available CMIP3 models was undertaken, assessing their ability (when downscaled) to capture the broad 20th century climate pattern of New Zealand. This has led to the 'best' 12 of the models being used to develop nationally consistent projections for mean monthly rainfall and temperature. These projections have been reported as guidance for local Government (see, MFE 2008) and are the core basis for planning around climate change in New Zealand[7]. They are based on monthly data, with base calculation being a set of average changes to monthly averages for 2040 (2030–49) and 2090 (2080–99), compared to a base climate of 1980–99.

4.2.1 Temperature and rainfall

Figures 2.13 and 2.14 show the projected annual temperature and precipitation change for 2040 and 2090. Figure 2.15 shows the projected seasonal precipitation changes for 2090. The projections are 12-model averages for the mid-range emissions scenario (A1B). They represent a central value of a range of models and emission scenarios, which could arguably be considered the 'most likely value' but masks changes in extremes particularly for precipitation (Knutti et al. 2010).

For temperature, these New Zealand projections track at around 0.25°C to 0.50°C below the global average, because of the buffering effect of the surrounding oceans and the tendency of the oceans to the south of New Zealand to warm much more slowly than the global mean. The spatial pattern for temperature change is relatively smooth and uniform across the country (Figure 2.13).

A consistent signal from global climate model projections is for an increase in the westerly wind circulation over New Zealand, especially in winter and spring. During summer, there may be a tendency for reduced westerly winds over New Zealand, but this is less certain (Mullan et al. 2008).

As a result of expected wind changes, an increase in annual mean precipitation in western regions of New

[7]A summary of the nationally consistent projections can also be found at: http://www.niwa.co.nz/our-science/climate/information-and-resources/clivar/scenarios (accessed 15 June 2012).

Zealand is projected along with a decrease in rainfall in the east of the country. Such changes are projected to be most pronounced in winter and spring. This is an overall intensification of the 'Foehn effect' (Section 3.1), with changes to the frequency (risk) characteristics of rainfall and evaporative events down the East Coast. During summer, there may be a reversal of this trend, with somewhat increased rainfall in the east of the country, and decreases in the west (Mullan et al. 2008). There is also an important change to projected northern North Island rainfall, primarily due to the expansion of the subtropical highs.

The box plots of council district change in Figure 2.16 establish that there is also a range in temperature projections given AOGCM model variability for New Zealand, generally of between 1°C and 4°C. Generally, the interquartile range is smaller for the northern and central areas, indicative of greater confidence in the projections. The range is wider for the South Island, particularly for Southland, Otago and the West Coast, consistent with the differing abilities of the models to capture Southern Ocean processes.

The ranges for annual precipitation changes (Figure 2.17) show that that there are differences in the direction of change, depending on the AOGCM. While the median value quantifies the 'most likely' outcome for each council district (as mapped in Figure 2.14, the 10–90th percentile range and in some cases the interquartile range suggest either positive or negative precipitation changes are possible in all districts. Despite this, there are stronger consistent negative signals (average decreases) for Northland, Auckland, and Gisborne, with the entire interquartile range being negative. Conversely, Southland, Otago, West Coast, Tasman, Marlborough and Taranaki have consistent positive change (average increases) across the range of model output.

For the remaining districts the range of outcomes spans both positive and negative precipitation change. An important example is the Canterbury region, where the most likely change is for a 7–8 per cent annual precipitation decrease, but the interquartile range is wide, indicating a distinct possibility of increasing precipitation. Although the processes are yet to be formally studied, this may be due to differences between AOGCMs in simulating the strength of changes in the westerly wind circulation (and subsequently a wide range in estimation of the 'spill-over' effect across the Southern Alps).

There are also differences between projections given different scenarios of global GHG emissions. Pattern scaling factors have been calculated for New Zealand, and are: 0.65 (A1B to B1); 0.85 (A1B to B2 and A1B to A1T), 1.21 (A1B to A2) and 1.44 (A1B to A1FI). These scaling factors can be directly applied to the temperature and can also be applied to the precipitation after these data have been converted from percentages to actual changes (in mm). Table 2.2 illustrates the range in annual temperature projections for 2080–99 for each district council, given future emissions scenarios and AOGCM model range [lowest, highest].

There have also been a number of studies which extend temperature projections to agro-climatic indexes that effectively have more relevance for primary production. One is the use of growing degree days, which point to changes in the development time of key crops like grapes (Tait 2008). At present, work is underway to identify impacts for the primary sectors if the global average temperature increased by 4°C. More detail about these temperature responses is given in Chapters 3-7.

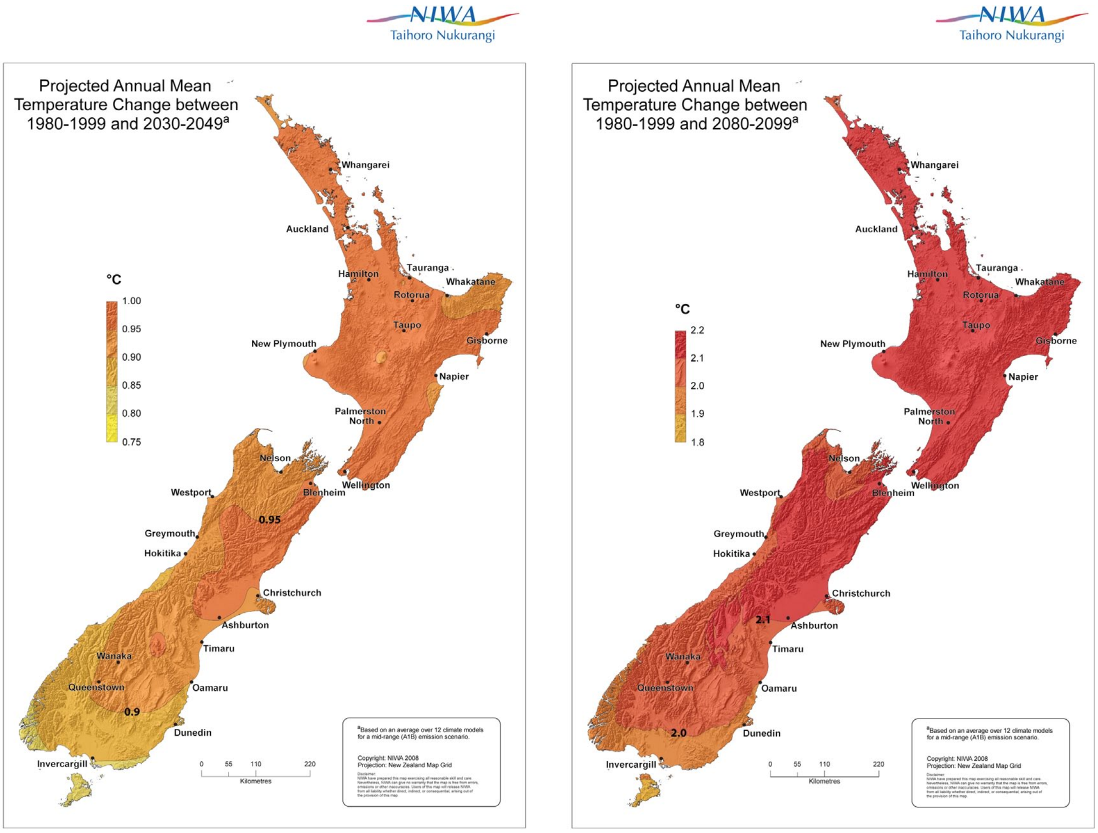

Figure 2.13. Projected mean annual temperature change (°C) for 1980–1999 and 2030–2049 (left); and 2080–2099 (right). For A1B scenario, average is from 12 downscaled AOGCMs.

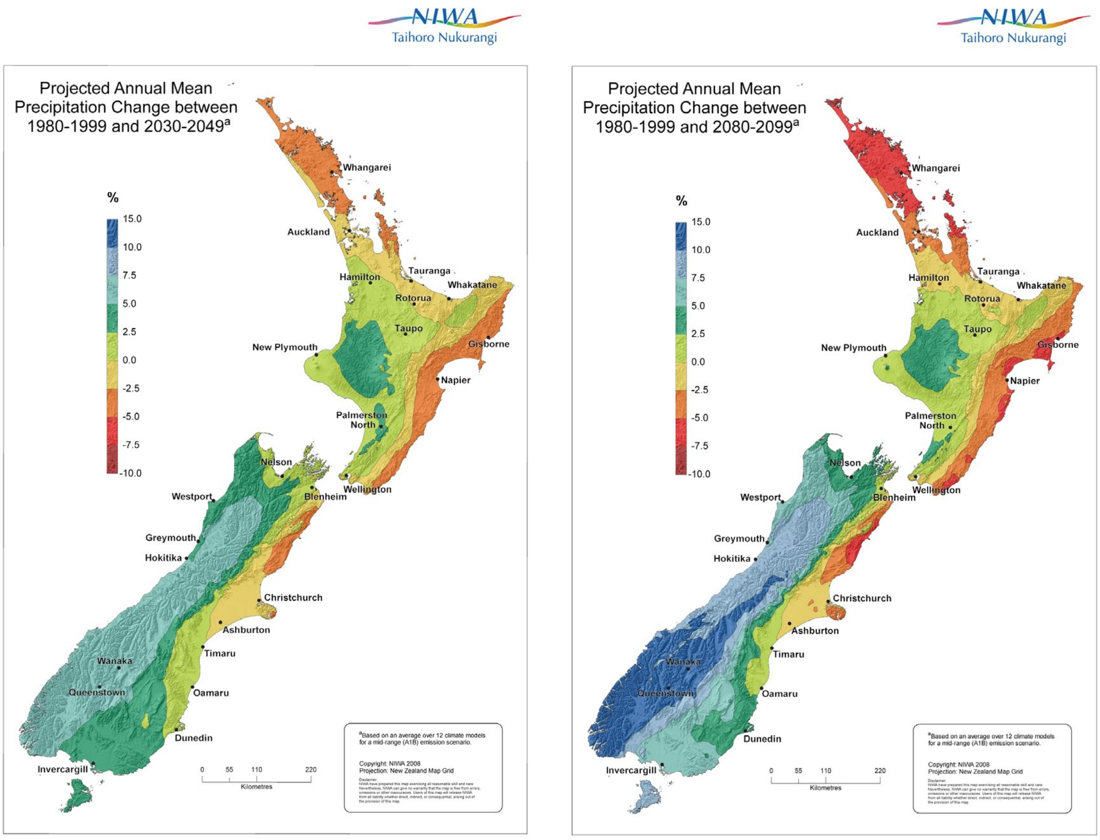

Figure 2.14. Projected mean annual precipitation change (per cent) for 1980–1999 and 2030–2049 (left); and 2080–2099 (right). A1B scenario is averaged from 12 downscaled AOGCMs.

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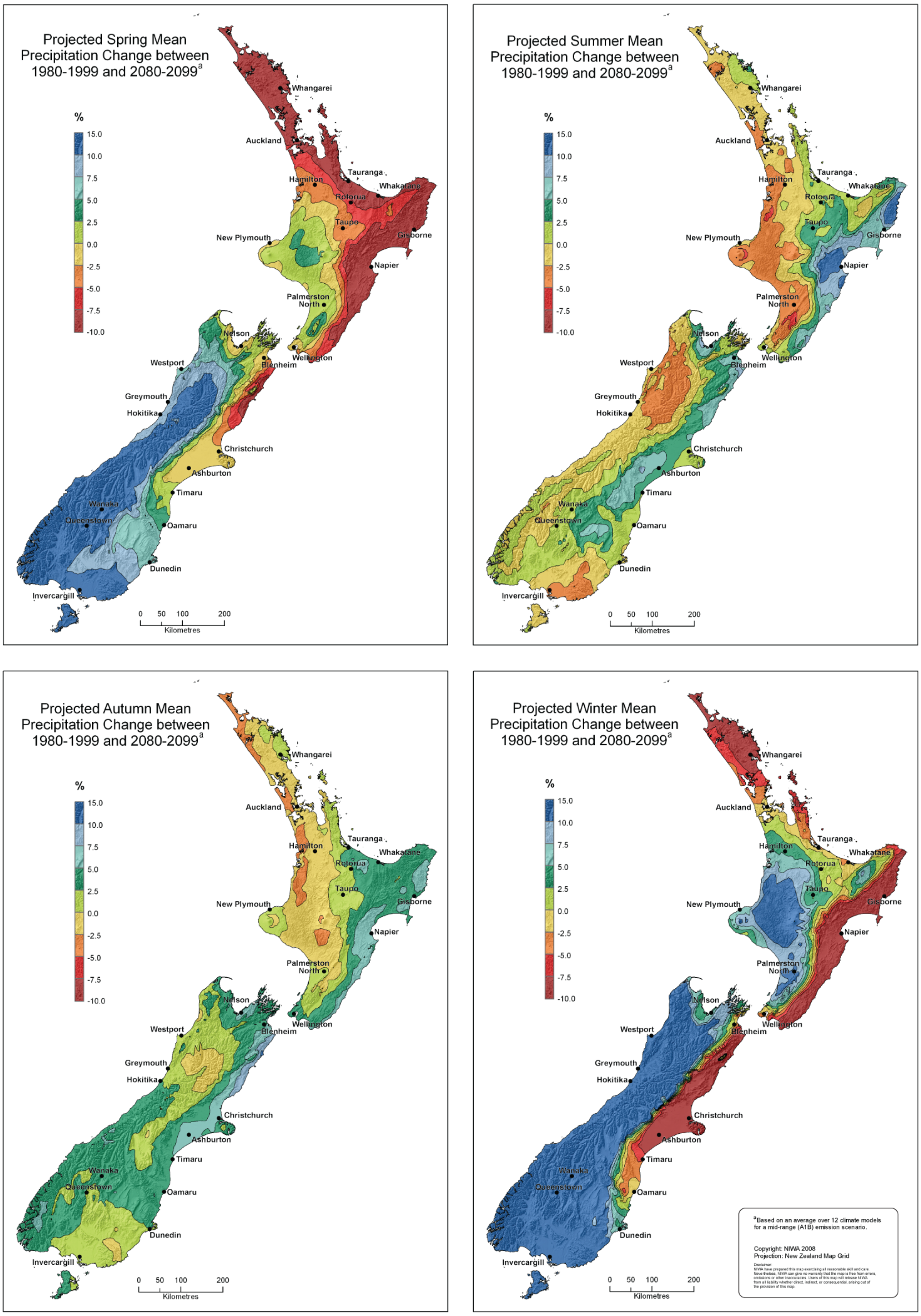


Figure 2.15. Projected mean seasonal precipitation change (per cent) for 1980–1999 and 2080–2099. A1B scenario is averaged from 12 downscaled AOGCMs.

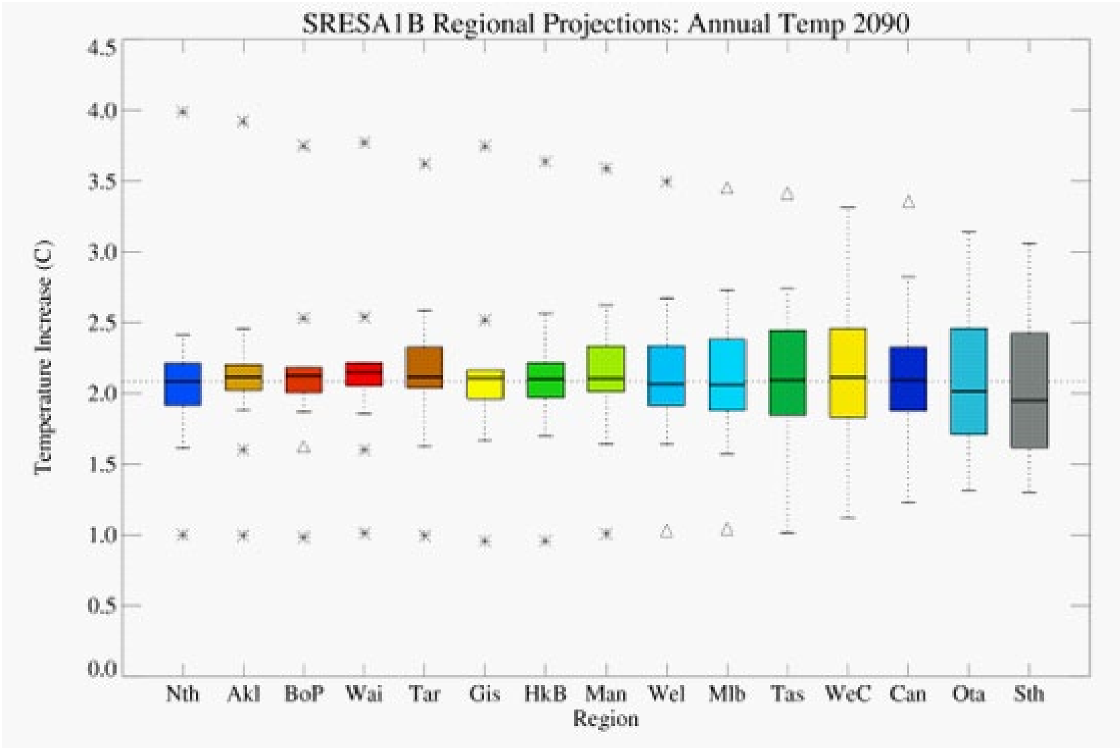


Figure 2.16. Inter-model range in mean annual temperature projections (°C increase from 1980–99 climatology) for regional council areas in New Zealand. Thick lines are the median; boxes are the interquartile range (25–75th percentile), whiskers are the 10–90th percentile range, and asterisks and triangles are outliers. The horizontal dotted line across all regions marks the national-average median temperature change.

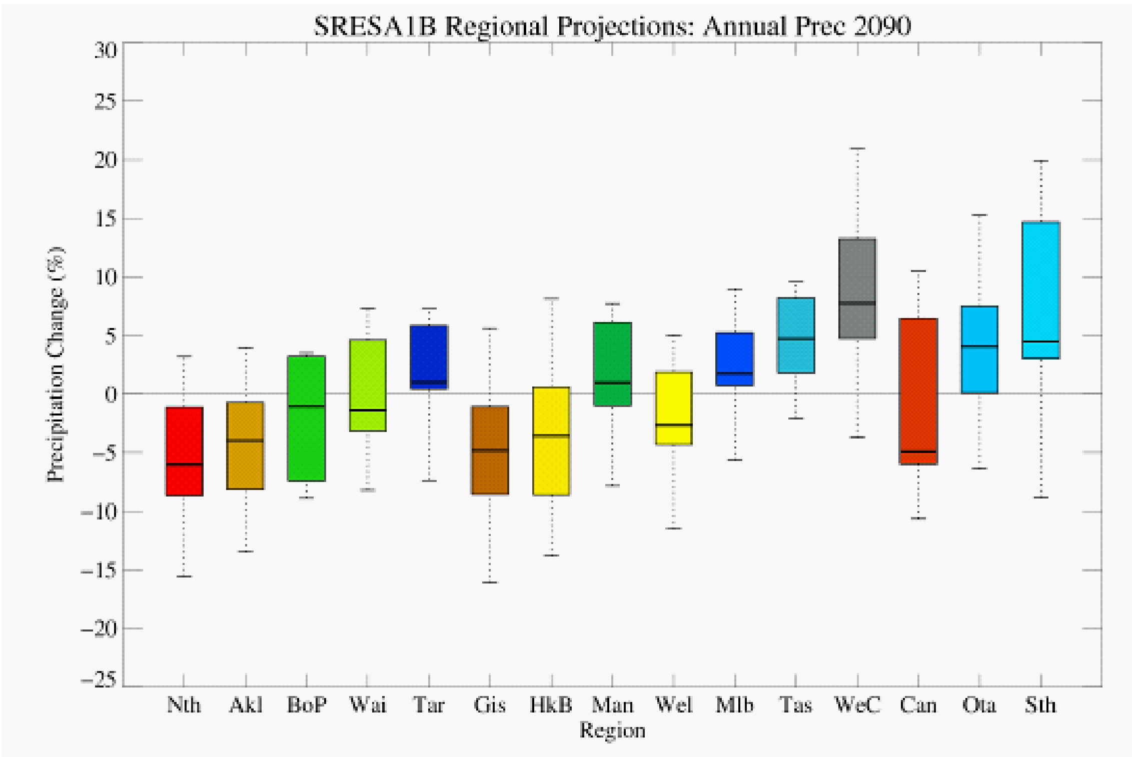


Figure 2.17. Inter-model range in mean annual precipitation projections (percentage of 1980–99 climatology) for regional council areas in New Zealand. Graph components as for Figure 2.16.

Table 2.2. 2080–2099 projected annual temperature change (°C) for each Regional Council region by emissions scenario. Range across global climate models is reported as (mean [lower, upper]).

Regional Council Region	***Scenario***				
	B1	***A1T/B2***	***A1B***	***A2***	***A1FI***
Northland	1.3 [0.6, 2.7]	1.7 [0.7, 3.5]	2.1 [0.9, 4.1]	2.5 [1.1, 5.0]	3.0 [1.3, 5.9]
Auckland	1.4 [0.6, 2.6]	1.8 [0.7, 3.4]	2.1 [0.9, 4.0]	2.5 [1.1, 4.9]	3.0 [1.3, 5.8]
Bay of Plenty	1.4 [0.6, 2.5]	1.8 [0.7, 3.3]	2.1 [0.9, 3.8]	2.5 [1.0, 4.7]	3.0 [1.3, 5.5]
Waikato	1.4 [0.6, 2.5]	1.8 [0.8, 3.3]	2.1 [0.9, 3.8]	2.5 [1.1, 4.7]	3.0 [1.3, 5.6]
Taranaki	1.4 [0.6, 2.4]	1.8 [0.7, 3.2]	2.1 [0.9, 3.7]	2.5 [1.1, 4.5]	3.0 [1.3, 5.3]
Gisborne	1.3 [0.6, 2.5]	1.7 [0.7, 3.3]	2.1 [0.9, 3.8]	2.5 [1.0, 4.7]	3.0 [1.2, 5.5]
Hawke's Bay	1.3 [0.6, 2.4]	1.7 [0.7, 3.2]	2.1 [0.9, 3.7]	2.5 [1.0, 4.5]	3.0 [1.2, 5.4]
Manawatu	1.4 [0.6, 2.4]	1.8 [0.8, 3.2]	2.1 [0.9, 3.6]	2.5 [1.1, 4.5]	3.0 [1.3, 5.3]
Wellington	1.3 [0.6, 2.3]	1.7 [0.8, 3.1]	2.1 [0.9, 3.6]	2.5 [1.1, 4.4]	3.0 [1.3, 5.2]
Marlborough	1.3 [0.6, 2.3]	1.7 [0.8, 3.0]	2.0 [0.9, 3.5]	2.5 [1.1, 4.3]	2.9 [1.3, 5.1]
Tasman	1.3 [0.6, 2.3]	1.7 [0.8, 3.0]	2.0 [0.9, 3.5]	2.5 [1.1, 4.3]	2.9 [1.3, 5.0]
West Coast	1.3 [0.7, 2.2]	1.7 [0.8, 2.9]	2.0 [1.0, 3.4]	2.4 [1.2, 4.1]	2.9 [1.4, 4.9]
Canterbury	1.3 [0.7, 2.2]	1.7 [0.9, 2.9]	2.0 [1.1, 3.4]	2.5 [1.3, 4.2]	2.9 [1.6, 5.0]
Otago	1.3 [0.8, 2.1]	1.7 [1.0, 2.8]	2.0 [1.2, 3.2]	2.4 [1.4, 3.9]	2.8 [1.7, 4.6]
Southland	1.3 [0.8, 2.0]	1.6 [1.0, 2.7]	1.9 [1.2, 3.1]	2.3 [1.4, 3.8]	2.8 [1.7, 4.5]

4.2.2 Drought

Larger scale agriculture droughts are more amenable to climate model analysis than daily or hourly weather extremes, as they occur over longer durations and can be quantified to some extent using monthly data. Mullan et al. (2005) used the national projections to develop future scenarios of drought. The study employed a change factor analysis to derive daily climate time series for a soil-water balance, given the on average monthly projected changes (formerly termed 'temporal downscaling'). The water balance utilises changed evaporation estimates, thereby estimating the combined effects of temperature and rainfall changes. Using AOGCMs from the TAR return period, drought statistics were calculated under 'low-medium' to 'high-medium' climate scenarios (individual AOGCMs from the A1B emissions scenario only).

The study found that drought risk is expected to increase during this century in all areas that are currently drought-prone, under both the 'low-medium' and 'medium-high' emissions scenarios. Generally, the study reinforced the higher exposure to changes in precipitation on the East Coast, as shown in Figure 2.15 for seasonal rainfall. Under the 'low-medium' scenario, a 1-in-20-year drought calculated from 1980–99 base period is expected occur at least twice as often by 2080 in some key agricultural regions, notably inland and northern parts of Otago; eastern parts of Canterbury and Marlborough; parts of the Wairarapa; parts of Hawke's Bay; parts of the Bay of Plenty; and parts of Northland.

4.3 Emerging projections

The national projections were developed using one approach to downscaling New Zealand's climate, given information from global models. However, the basis for developing regional scale projections is changing as new methodologies are developed. These changes to underlying methodology are required to include more process information into the downscaling, and to improve baseline knowledge over time – as well as the plausibility of the projections. The aim is to develop more locally specific knowledge particularly around plausible changes to extremes.

Two methods are commonly used for downscaling, Empirical-Statistical Downscaling (ESD) and Regional Climate Modelling (RCM). In RCM, the Global Circulation Model (GCM) provides boundary conditions for a limited area physical model. In ESD, broadscale climate predictors are related to 'predictands' (both observations) by empirical transfer functions which are then applied to projections from GCMs. There are strengths and limitations in both approaches (Benestad 2008). In general, RCM provides a more physically plausible basis for projections, but is limited in terms of the time it takes to set up and produce simulations, which are generally confined to one GCM. ESD provides a more timely basis for producing projections and allows many GCMs to be utilised (ensemble methods), but does suffer from 'stationarity' assumptions that limit inferences that can be made.

In New Zealand both approaches are actively pursued. While ESD provides a more flexible and timely basis for developing projections, the assumption of stationarity is an important factor in the New Zealand setting. It means (in the case of ESD) that the relationships and physical processes that govern climate do not fundamentally change in the future. This assumption may not hold given feedbacks and non-linearity in the regional climate system. This limits the confidence of projections based on ESD, particularly around extremes (Box 2.5) and in localised environments. Despite this, much of the inference about future climate in New Zealand over the last decade has been based on ESD (Kenney et al. 1995; Mullan et al. 2008; Renwick et al. 2009; Clark et al. 2011).

4.3.1 Empirical projections of drought

The drought study of Mullan et al. (2005) has been updated by Clark et al. (2011) using a new approach to ESD which supports the analysis of variability, at least on a month-by-month basis. The study examined a broader range of the 'scenario space' (models and emissions scenarios) available through CMIP3 to be analysed than previously.

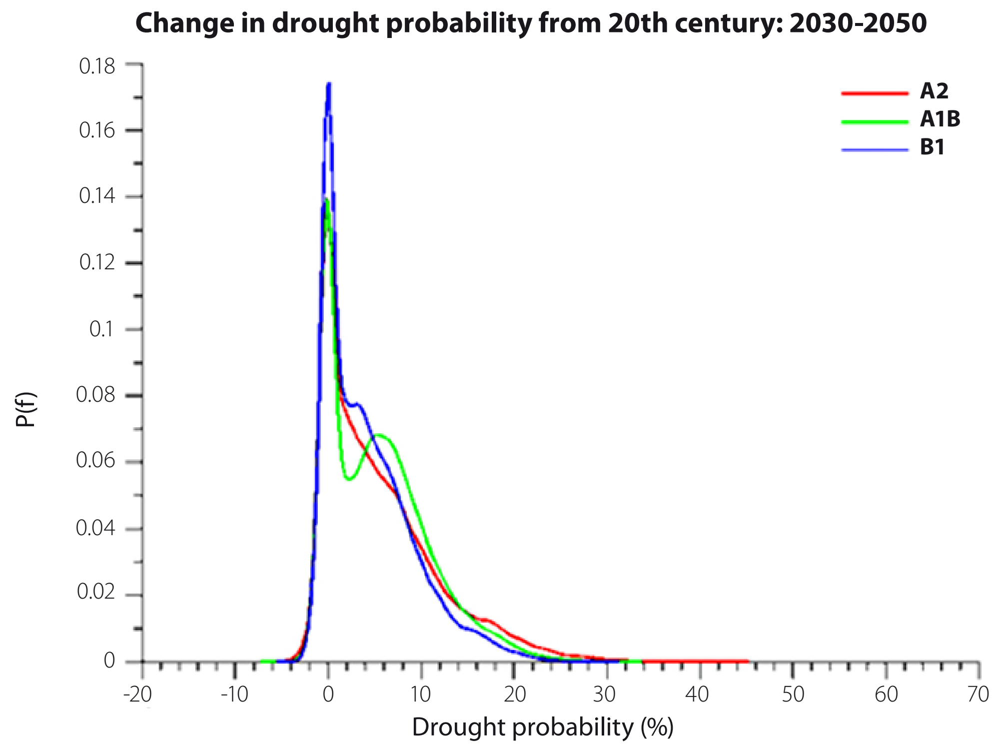
Clark et al. (2011) found the general east-west gradient in change to drought risk quantified by Mullan et al. (2005), a result of an intensified Foehn effect. However, the range of plausible outcomes quantified is much wider than found previously for New Zealand. Clark et al. (2011) condensed this range into a set of mid-century planning scenarios for consideration by decision makers:

- A ***more likely scenario*** with around ten per cent additional time spent in drought (from the 1980–99 baseline) by the middle of this century for key eastern agricultural regions.
- A ***less likely upper scenario*** for the middle of this century range with a strong shift toward a more drought-prone climate over most agricultural regions with well over a doubling of time spent in drought across most of New Zealand.
- A ***less likely lower scenario*** with small increases from current levels of drought frequency, isolated to eastern agricultural regions only.

By the end of the this century, this set of projections show that much of New Zealand's agricultural zone would experience some increase in drought, even under the milder scenario. The quantitative results of this study are described in Box 2.6.

Box 2.6. Quantitative estimates of the range of change in drought for New Zealand.

The range of results found in a recent study of change in drought (Clark et al. 2011) are summarised by the probability density functions in Figure 2.18. The difference between the B1 (lower) and the A1B (mid) and A2 (higher) emissions scenarios suggest that there are potential benefits in global mitigation for New Zealand. By the mid century, there are small reductions in change to drought risk if a lower emissions (B1) mitigation pathway is taken. By the end of the century, a B1 global emissions pathway results in a much less drought-prone environment than the A1B and A2 scenarios.



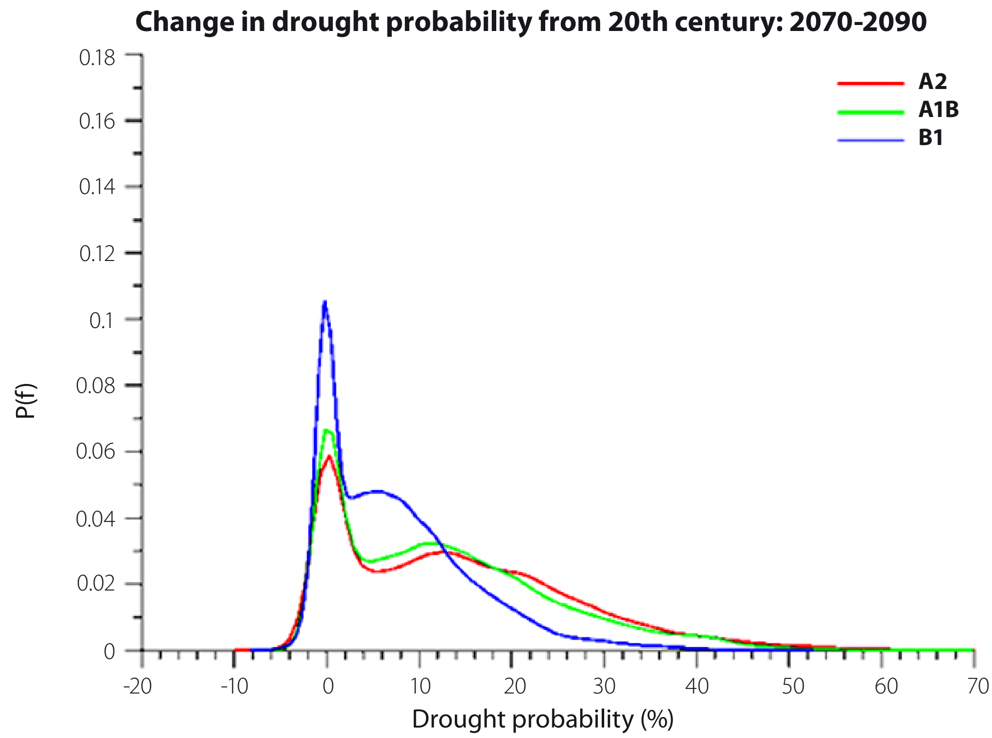


Figure 2.18. Probability density functions of projected changes to drought probabilities across agricultural land for 2030–2050 (top) and 2070–2090 (bottom), from Clark et al. (2011).

The drought projections for the A1B emissions scenario are broken down by sector in Figure 2.19, quantifying exposure of primary industries based on 2007 land use patterns. The average drought exposure increases across all sectors, and for the most part there is remarkably even exposure. The exception is the arable cropping sector which has a greater degree of additional time spent in drought in both 2040 (2030–50) and 2080 (2070–90).

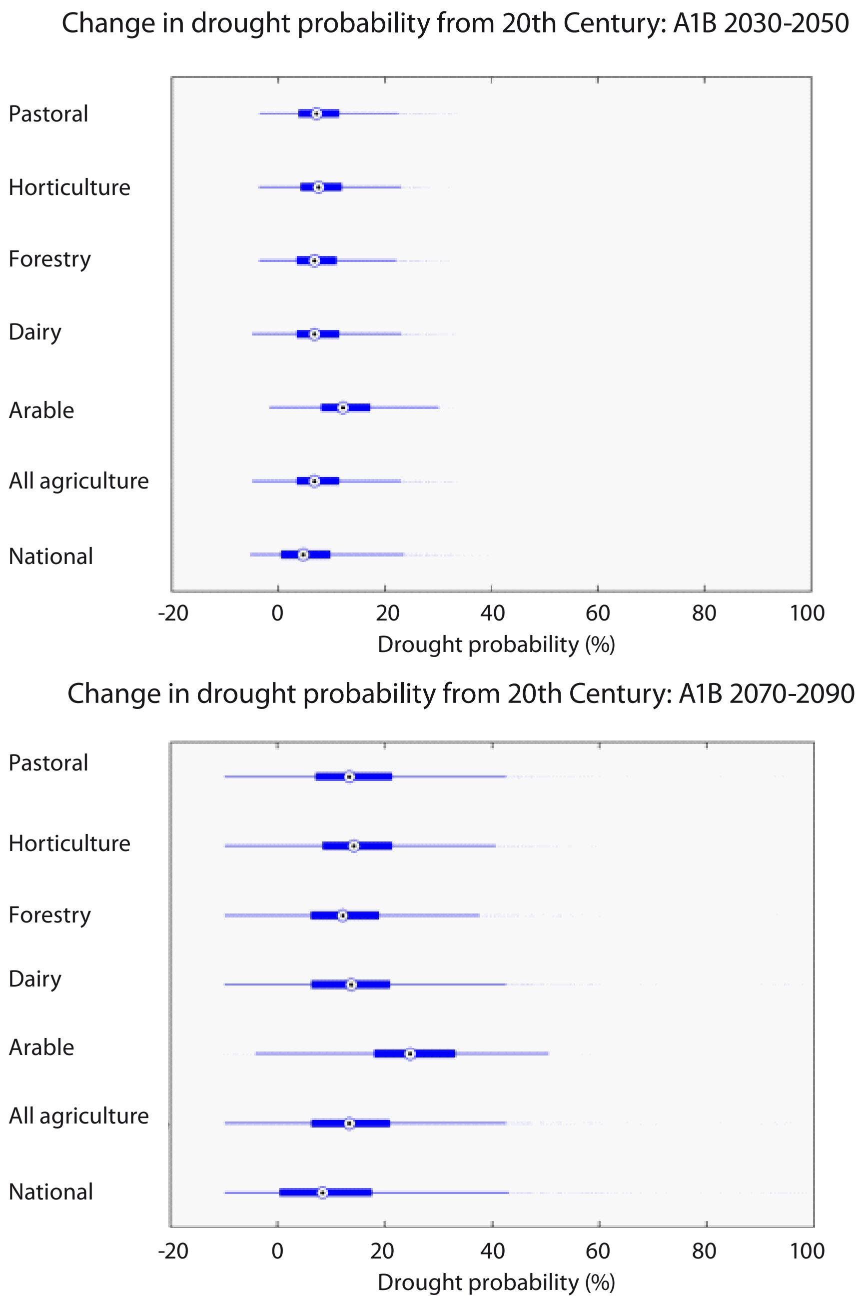


Figure 2.19. Range of projected changes in drought probability for each sector based on current (2007) land use patterns. Changes represent addition time spent in drought from the 1980–99 base period. Mid-point is the median of the GCM ensemble with solid bars showing the inter quartile range (25th–75th percentile). Lines are the 10th–90th percentile. Outliers shown as dots. Clark et al. (2011).

The projections for the SRES A1B scenario in Figure 2.19 also span a considerable range. At one extreme there are increases of the order of 20 per cent more time spent in drought by 2040, through to 40 per cent by 2080. Given that current (1980–99) drought exposures are, at worst, 10–15 per cent in east coast regions, this is well over a doubling of time spent in drought in some regions. Conversely, there are also reductions in time spent in drought for a smaller proportion of land across all sectors, of the order of minus 5 per cent in 2040 through to minus 10 per cent in 2080.

4.3.2 Regional climate modelling

Improving the understanding of the complex relationships between the processes that drive regional variability and physical laws like the Clausius-Clapeyron relationship under a warming global environment is crucial in the

New Zealand context (Box 2.5). A key approach to improving this understanding is the application of physically based models to study the local regime, or regional[8] climate models. These have not been used widely to study regions under climate change (Stott et al. 2010), but there has been an increase in their application since the release of the AR4 in 2007. Over time, more rigorous treatment of changes to variability and extreme events should be possible than currently available. This is important as these events are often stronger drivers of impact in the primary sectors than the average changes reported in the nationally consistent projections.

New Zealand has a strong history in the application of regional scale models across a number of applications like air pollution assessment, weather and hazard prediction, and climate analysis. For example the Weather Research and Forecasting (WRF) community model has been used for some time by (the NZ) MetService as an active forecasting tool and by climate researchers. A recent example is provided by Powell et al. (2011) who examined micro-climatic variability in Marlborough grape growing regions. The study found that fine scale spatial variability (micro-climates) may be greater than inter-annual variability or the climate change signal.

NIWA has set up a high-resolution climate modelling system specifically to research the complex processes and interactions that occur in the New Zealand under global climate change. Known as the Regional Climate Model (RCM), the system is a version of the United Kingdom Meteorological Office (UKMO) unified model. This system is a global climate model (HADCM3 then later HadAM3P) coupled with the UKMO regional climate model (PRECIS) configured for New Zealand conditions (Bhaskaran et al. 2002).

The RCM was first run in 2008–09 using HADCM3 for the global model, producing an initial set of simulations for the period 1970–2000 and the SRES A2 emissions at 2070–90 (termed RCM Set-1 simulations in this report). These initial runs have been used for extensive model testing and development. Some scientific analysis has also been undertaken using the simulation results, and has provided a number of new insights:

- Carey-Smith et al. (2010) confirmed the operation of Clausius-Clapeyron relationship in the New Zealand system. The interactions with synoptic processes suggest that the increases in extreme rainfall amounts may be even higher than those based on predictions from the physics alone, due to a combination of thermal and dynamical effects.

- As part of a more extensive analysis on extreme wind changes, Mullan et al. (2011) analysed the wind fields using a mix of severe weather indices. These show increases in the frequency of severe weather events over much of the New Zealand domain in a future climate that is approximately 2°C warmer than present. This demonstrates that vigorous small-scale convective events can be more common and more intense in a future warmer climate. However, further work would be required to relate these severe weather indices to quantitative changes in extreme surface winds.

- McMillan et al. (2010) used RCM Set-1 scenarios to drive hydrological models and asses flood extremes in three small test catchments. It was the first study to utilise RCM simulations in a downstream 'impact model', highlighting greater frequency and magnitude of severe flood events in a warming climate. This study is described in more detail in Chapter 8.

The model testing and development based on the Set-1 RCM simulations highlighted deficiencies with the RCM in representing atmospheric processes, external forcing, local surface conditions and the atmospheric state. These lead to the types of systematic biases that are well known in many RCM applications (Benestad 2008), such as to many small rainfall events. To ensure the system is more useful for both research on processes and scenario development for decision makers, a number of aspects of the model were improved. These improvements included: a new computing environment; a change of the GCM from from HADCM3 to HadAM3P; improved physical detail; and application of bias correction techniques.

In 2011 the full model system was run twice for each global emissions scenario (A2, A1B and B1). These are called RCM Set-2 (June 2011) and Set-3 (December 2011) simulations in this report. They cover a 130-year period (1970–2100), providing daily weather data at about 300 grid-points (~ 30km^2 grid) over the New Zealand land mass. The two sets of simulations are nearly identical, differing only in minor technical details, with the latest version (Set-3) being considered more consistent and reliable. Work of this nature is ongoing, and more simulations are being run to build a larger ensemble of outcomes.

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[8]'Regional' in climate modelling means a land mass from sub-continental to national scale or below. In the New Zealand context this is approximately a whole of country model with a resolution of 5-30 km^2, capable of resolving processes unique to land areas approximated by regional and district council boundaries, and some of the topographic variability within these municipalities. This is technically known as 'meso scale'. Below this is 'micro scale' which is modelling around a single farm area or below, to individual paddocks.

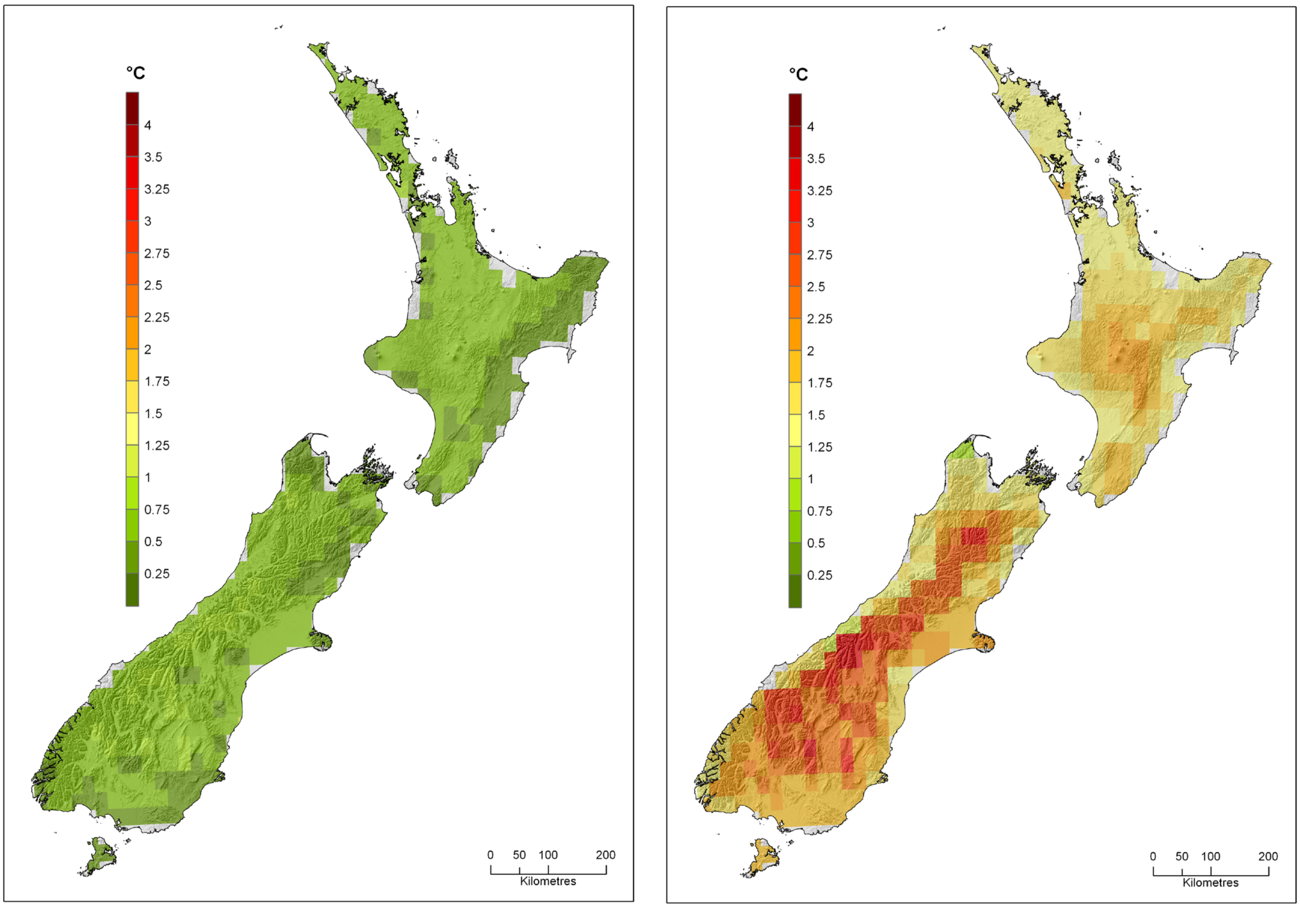


Figure 2.20. Changes in maximum temperature projected by the RCM Set-3 simulations for the A1B emissions scenario. (a) Projections for 2030–49 relative to 1980-99. (b) Projections for 2080–99. All data are bias corrected.

Summary analyses from the RCM Set-3 simulations are shown in Figure 2.20. These highlight average changes within the range identified in the nationally consistent projections, with change in the order of +0.50°C to +0.75°C in 2040 with +1.25°C to +3.0°C changes in mean annual temperature in 2090. The spatial pattern of change is different, with a higher relative temperature change experienced across the Southern and Central Alps. The geographic pattern of change in precipitation is also similar to that in the 'most likely value' in the national projections (Figure 2.21. Generally these are wetter conditions on the west coast of the South island, and dryer to the north and east, more pronounced by 2090.

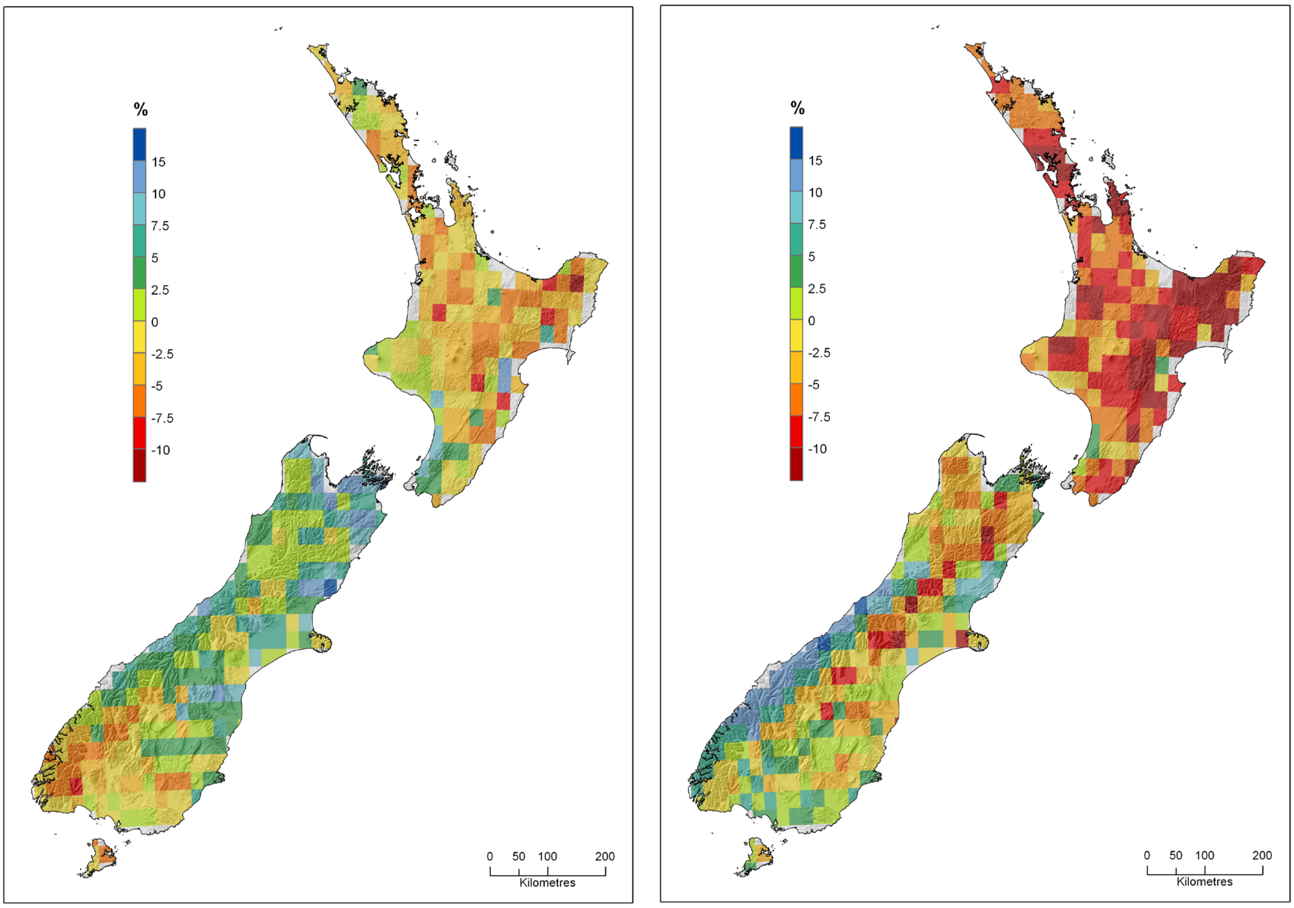


Figure 2.21. Annual mean precipitation changes projected by the RCM Set-3 simulations for the A1B emissions scenario. (a) Percentage change at 2030–49 from 1980–99. (b) Percentage change at 2080-99 from 1980-99. Data are bias corrected.

4.3.3 Scenarios for primary sector modellers

4.3.3.1 Technical development

Primary sector modellers who run detailed biophysical and management systems models have some specific requirements, and the availability of RCM simulations provides an opportunity to address some of the limitations in projected climate data (based on the national projections in Section 4.2[9]) that have been available to this community in the past. Specifically:

- Primary sector models require daily climate fields as inputs, to represent processes like plant growth (respiration and photosynthesis). The temporal downscaling technique used in previous projections to provide daily data masks potential changes in variability. It builds in the assumption that the mean and the variance change in a proportional way, which may not necessarily hold given complex regional climate processes. Utilising RCM output, which can be resolved directly at the daily time scale, offers a way of developing more physically plausible estimates about changes in future climate and production variability.
- The primary sector models require a broader suite of variables, beyond average temperature and precipitation changes than have been available in the past. Specifically they require daily rainfall, max and min temperature, radiation, potential evaporation and/or vapour pressure deficit, and wind run. These are available with careful treatment of RCM output.
- Production system modellers typically work on problems that are micro-meteorological in scale, with simulations isolated to an individual farm or paddock. Typically they look for data that is highly accurate at this scale so as to compare with measured estimates of production. The meso scale climate modelling in

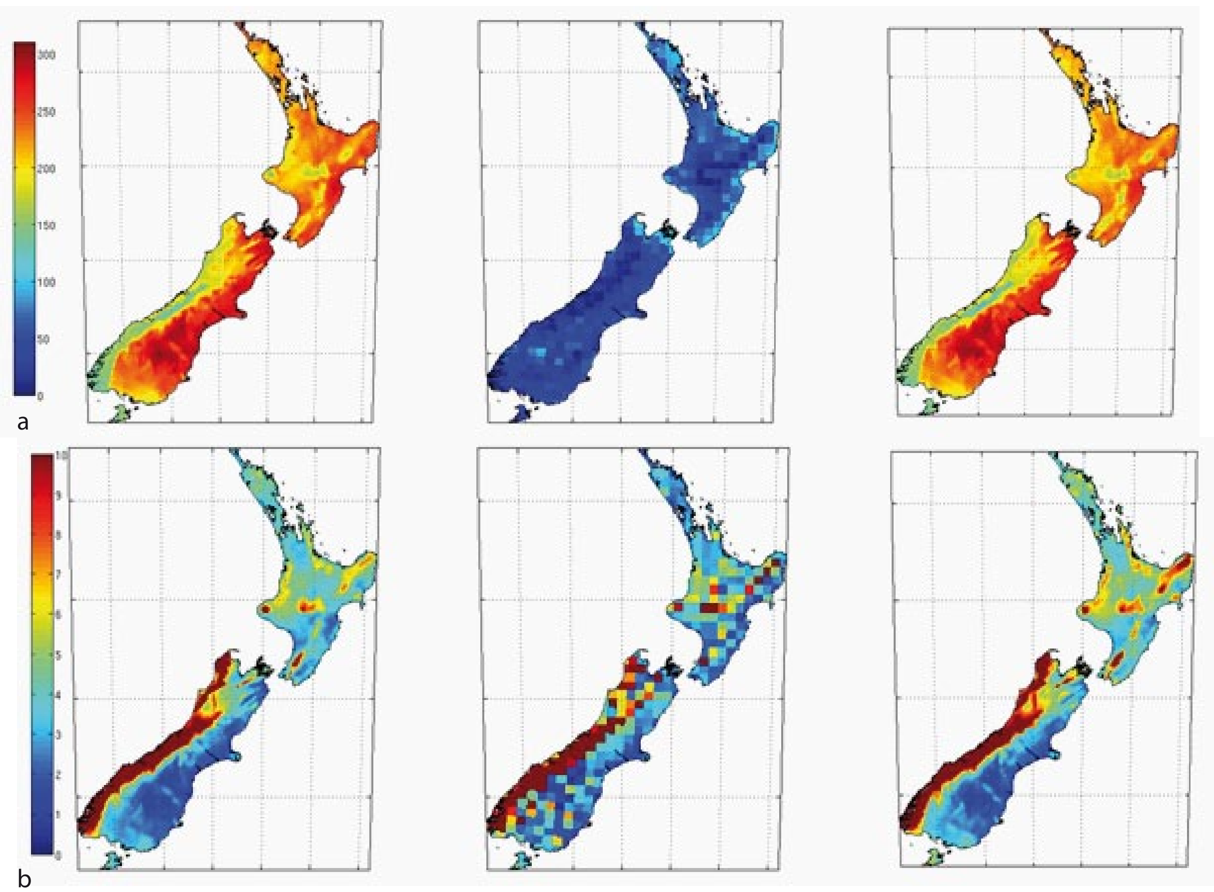
[9]These are based on a monthly change factor approach, which limits the representation of variability. These limitations are discussed in more detail in IPCC guidance material (Wilby et al. 2004).

RCM provides a significant step forward in resolving climate variability at this finer scale using a physically based approach. Although it is an improvement, this does not fully capture highly localised micro-meteorological processes, so some divergence is expected between RCM output (meso scale) and micro-meteorological observation data at an individual site (farm scale).

In consideration of these requirements a customised approach to bias correction with further downscaling was developed. Following a series of methodological trials a two-step bias technique was implemented, where: RCM fields within a 100 km^2 radius of a site were used to downscale variables to the micro-climatic level (individual site) using PLS regression; and the mean and standard deviation were bias corrected, given observations. Daily rainfall required additional treatment, where the event occurrence and rainfall amount were separated, the two-step technique applied, and the time series re-integrated. These techniques were applied in a way that preserves the relationships between the six climate variables, thereby providing primary sector modellers with internally consistent climate scenarios.

Figure 2.22 illustrates how the technique operates for daily rainfall when applied to every site across the country in the Virtual Climate Station Network (VCSN) data set. As shown, the RCM Set-2 simulations have similar broad spatial structure to observed rainfall amounts, but it underestimates the number of dry days over most of the country. As illustrated, the two step-bias technique was able to resolve the rainfall amount field at a finer spatial resolution (5km^2 grid) and also correct for this systematic bias in rain days.

The influence of the two-step technique when applied simultaneously across all variables is illustrated by output from a pasture growth model (Figure 2.23). In this case examples are from the Bay of Plenty. Some large biases between pasture growth rates derived from observed and untreated (nearest point) RCM Set-2 climate data are found. The RCM Set-2 derived series misses the timing of autumn in both examples (Figure 2.23 a, b), while



Observed **RCM (Set-2)** **RCM (Set-2) + Bias correction + downscaling**

Figure 2.22. Observed, simulated (RCM Set-2) and bias corrected/downscaled daily rainfall. (a) Mean number of zero (< 2mm) rainfall days. (b) Mean daily rainfall amount (mm) from 1-Jan-1990 to 31-Dec-1999. Observed are Virtual Climate Station data. Simulated are RCM Set-2 data.

the timing and magnitude of spring production are also missed in the inland site (Figure 2.23 a). Given the importance of timing in devising stock grazing practices, this would render subsequent analysis of adaptation uninformative if based on the 'raw' RCM Set-2 data. Although some minor differences remain, the two-step process applied to the RCM Set-2 data supported a more realistic simulation of pasture production timing and magnitude.

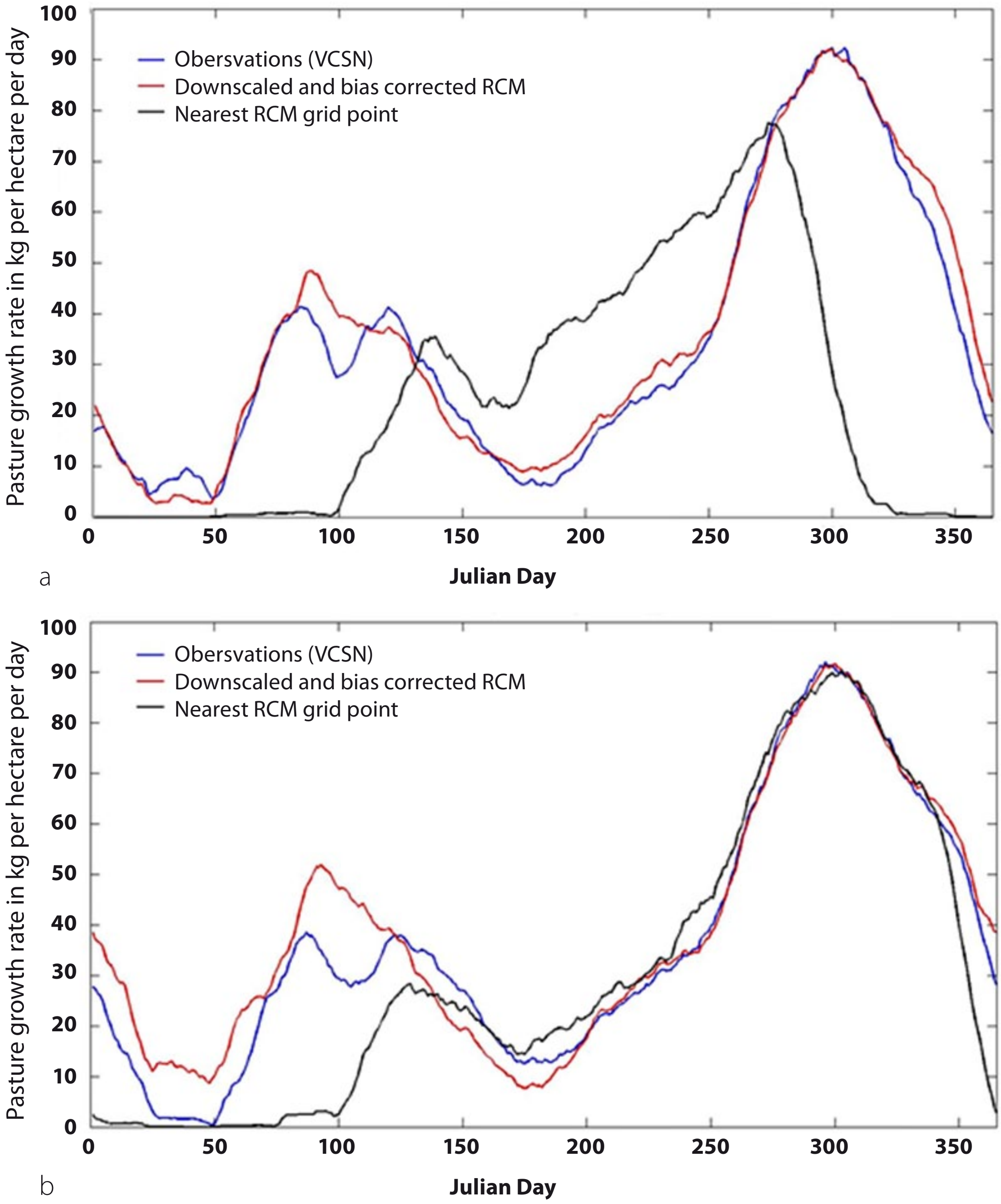


Figure 2.23. Pasture growth simulation driven by observed and simulated climate data for different sites. Pasture growth curves are averages of daily model output from 1990–99. (a) Inland Bay of Plenty. (b) Coastal Bay of Plenty. RCM data are from the Set-2 Simulation, where GCM scale input is derived from the National Centre for Environmental Prediction (NCEP) re-analysis.

4.3.3.2 Primary Sector Adaptation Scenarios (PSAS)

In addition to comprehensive science reviews, Chapters 3–8 present a range of impact and adaptation analyses using detailed biophysical and management models for each primary sector. Production system modelling of this nature requires significant investment in site establishment and testing if accurate and reliable estimates are required, particularly if management effects (adaptations) are assessed. This limits the number of sites and simulation experiments that can be practically carried out with these models. Hence, a full climate scenario and model ensemble study (as reported by Clark et al. 2011 for drought in Section 4.3.1) is not practical if detailed primary sector impact models are used.

To provide practical scenarios for primary sector adaptation analysis a more streamlined climate scenario design was developed. The range of future outcomes is simplified to a 'high and 'low' scenario at the mid-century time slice (2030–49, termed 2040). A more detailed discussion of the rationale for these choices is provided in Chapter 1.

The 'high' and 'low' scenarios were developed using the two-step downscaling procedure (Section 4.3.3.1) and the A2 and B1 Set-2 RCM simulations respectively. These are termed Primary Sector Adaptation Scenarios (PSAS). They are two plausible climate futures within the broader range of outcomes expected for New Zealand, as established by the previous nationally consistent projections and other emerging work (Sections 4.2 to 4.3.2).

A broad comparison of the PSAS and the broader range are provided in Table 2.3, and a comparison of national level changes are shown in Figure 2.24 and Figure 2.25. The main spatial patterns in the PSAS are mapped in Figure 2.26 and Figure 2.27 with the temporal pattern shown in Figure 2.28. These analysis quantify that the PSAS fall within the range of outcomes projected by the nationally consistent projections, where:

- The **high scenario ('A2')** has a +1.2°C change by 2040 (2030–49) starting from a 1980–99 baseline. National rainfall change is -1.8%, but the spatial pattern is a plausible but less likely outcome for New Zealand – for example a wetter North Island summer rainfall pattern.
- A **low scenario ('B1')** where there is a +0.89°C change by 2040 with a National annual rainfall change of +2.8%. The regional pattern is consistent with the more likely outcome in the nationally consistent projections for New Zealand, with drier eastern and northern summers.

The PSAS provide a mid- to high-end temperature change for the mid-century, when considering the full range quantified in the national projections (Section 4.2). They cover the broad range of seasonal and locational changes in rainfall. However, the PSAS also deliver what is best described a 'climate surprise', a wetter summer to the North Island in the high scenario. Even though the PSAS are based on one climate model, their use by detailed impact and adaptation analysts is consistent with the provision of climate planning scenarios. In these scenarios, the aim is to test across a range of plausible climate outcomes (Dessai et al. 2009), rather than basing strategies round the 'most likely' outcome of many climate models (Knutti et al. 2010).

Table 2.3. General comparison of the Primary Sector Adaptation Scenarios with the nationally consistent projections and emerging (RCM Set-1 and Set-3) projections.

PSAS	***Degree of change***	***Relative to other regional scenarios***
High scenario A2 emissions scenario at 2030–39	-1.81% change in mean annual precipitation +1.24°C change in mean annual temperature	• Higher degree of warming than Set-1 and Set-3 RCM simulations for the same period • Opposite sign and different spatial pattern of change to RCM Set-3 Simulations for summer precipitation in North Island • Mid-to-high (warmer) end of tempeature change range in Nationally consistent projections • Mid-to-low (dry) end of the range in nationally consistent projections. North Island summer precititation at the high (wet) end of the range for the North Island
Low scenario B1 Emissions Scenario at 2030–49	+2.14% change in mean annual precipitation + 0.89°C change in mean annual temperature	• Higher degree of warming than Set-1 and Set-3 RCM simulations for the same period • Precipitation: same sign of change to RCM Set-3 Simulations, larger increase than bias corrected RCM Set-3 • Middle of the tempeature-change range in nationally consistent projections • Mid-to-high (wet) end of the range in nationally consistent projections. Similar spatial pattern of change

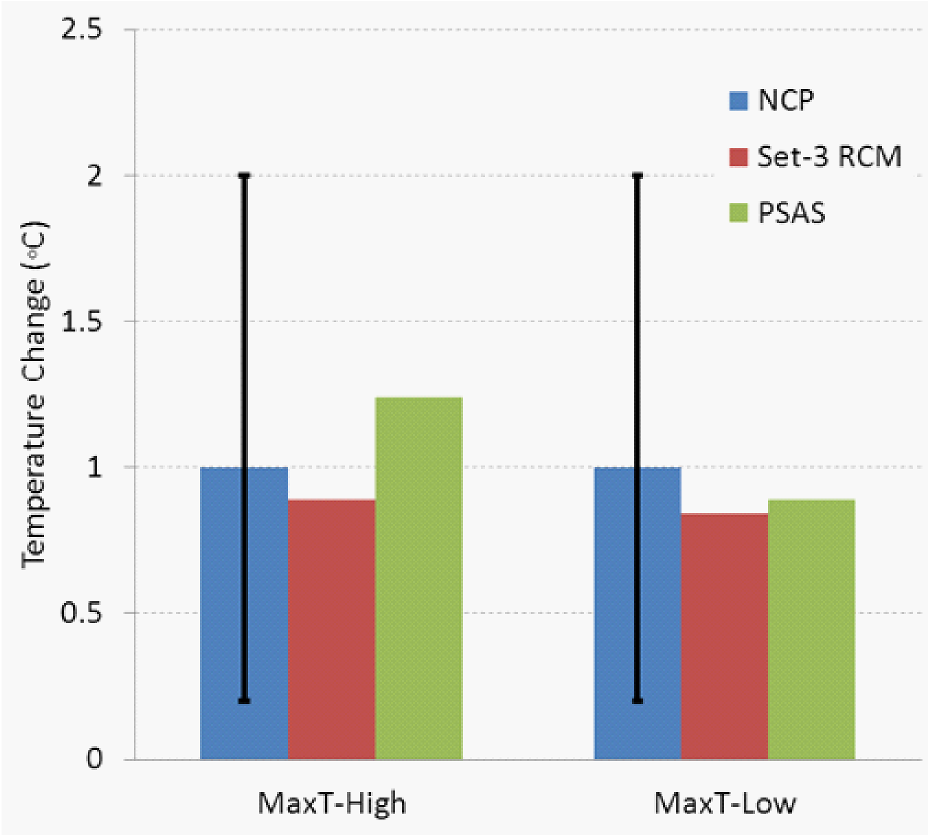


Figure 2.24. Comparison of climate change scenarios for change in maximum annual temperature aggregated across New Zealand. Changes are the degree change (°C) for 2030–2049 compared to 1980–99. NCP denotes Nationally Consistent Projections reported as the model mean (bar) and range (error bar) for the A1B emissions scenario (MFE 2008); Set-3 RCM denotes the most recent set of regional climate model simulations with bias correction. PSAS denote the Primary Sector Adaptation Scenarios (RCM Set-2 data with two-step downscaling and bias correction). Both RCM sets are for the high (A2) and low (B1) emissions scenario.

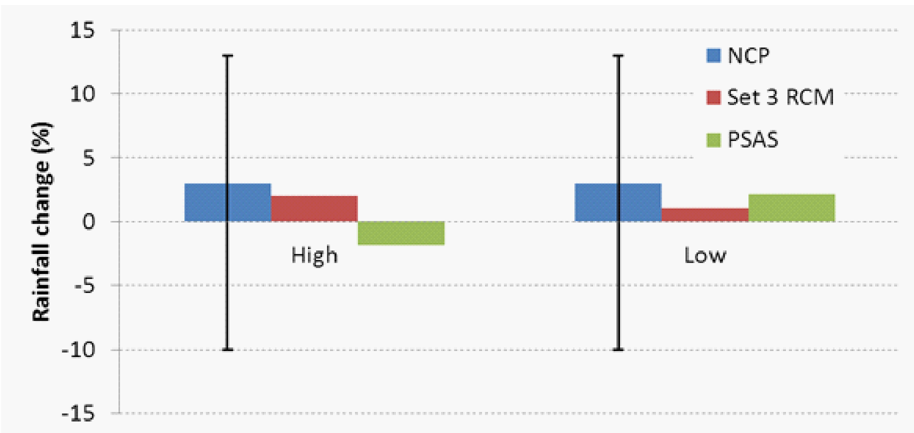


Figure 2.25 Comparison of climate change scenarios for change in annual rainfall aggregated across New Zealand. Changes are the percentage change from 2030–2049 compared to 1980–99. NCP denotes Nationally Consistent Projections reported as the model mean (bar) and range (error bar) for the A1B emissions scenario (MFE 2008); Set-3 RCM denotes the most recent set of regional climate model simulations with bias correction. PSAS denote the Primary Sector Adaptation Scenarios (RCM Set-2 data with two-step downscaling and bias correction). Both RCM sets are for the high (A2) and low (B1) emissions scenario.

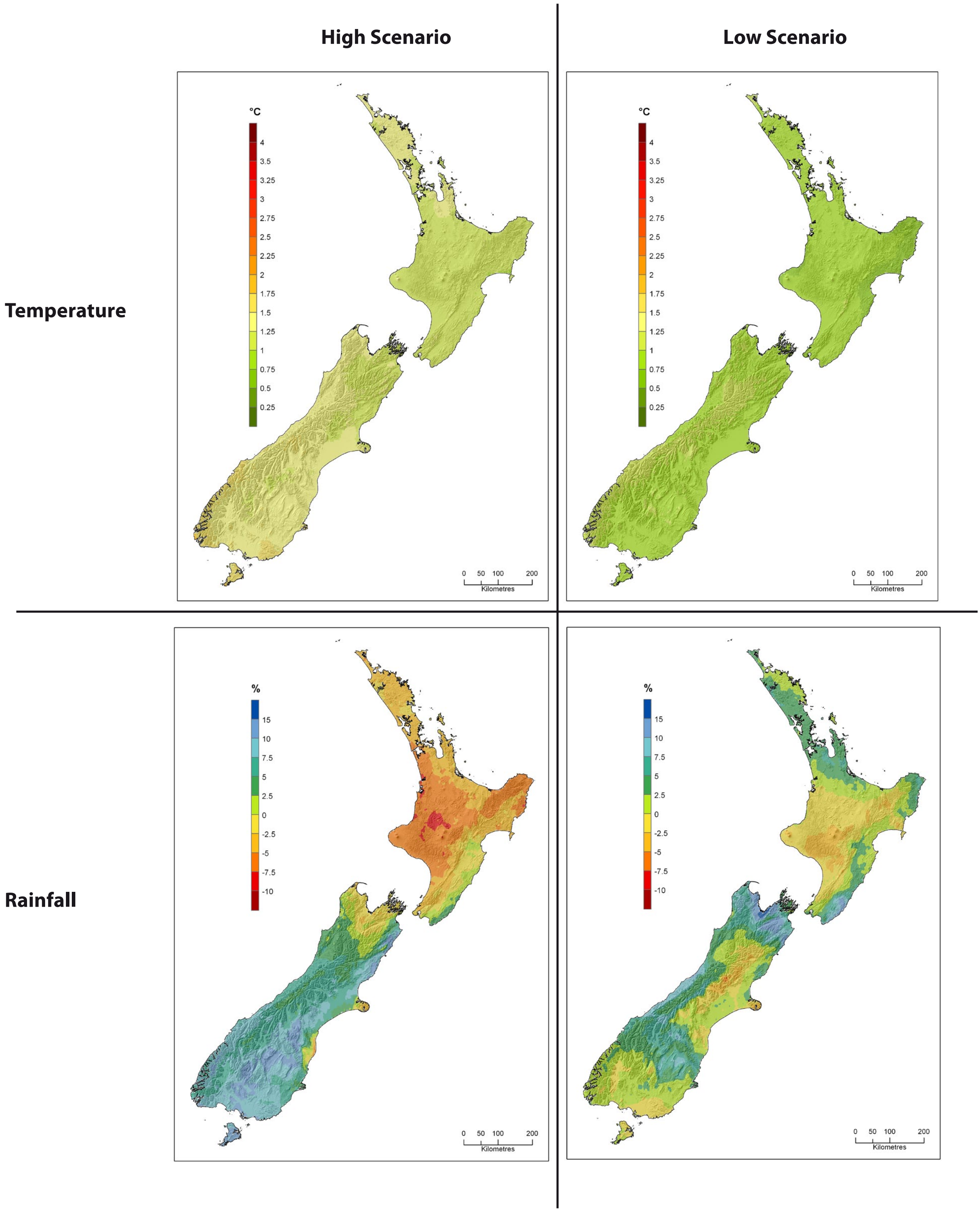


Figure 2.26. Spatial pattern of change for mean annual temperature (°C) and rainfall (percentage) in the high (A2) and low (B1) adaptation analysis scenarios at 2030–2049.

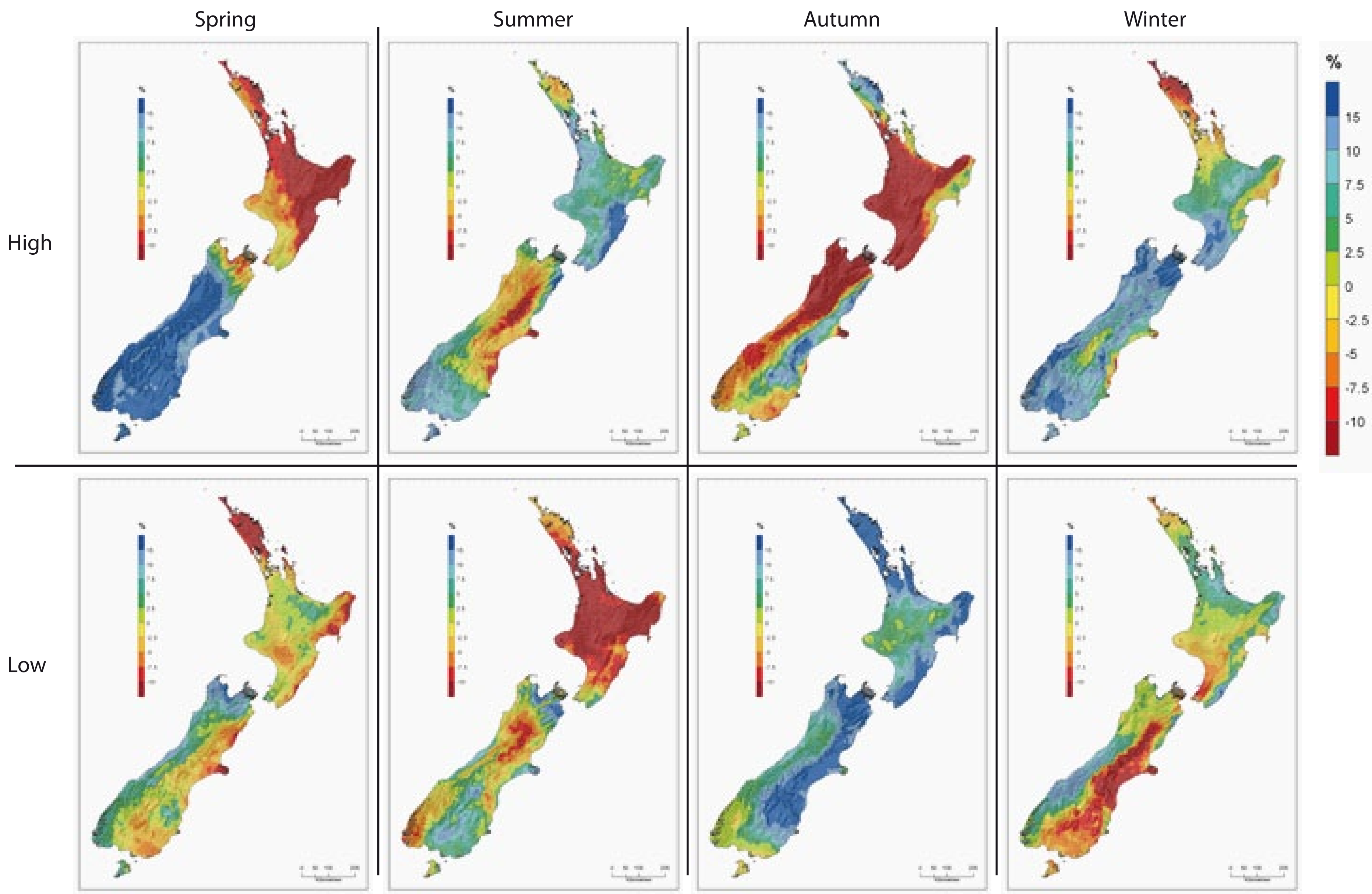


Figure 2.27. Spatial pattern of change for seasonal rainfall averages in the high (A2) and low (B1) adaptation planning scenarios at 2030-49.

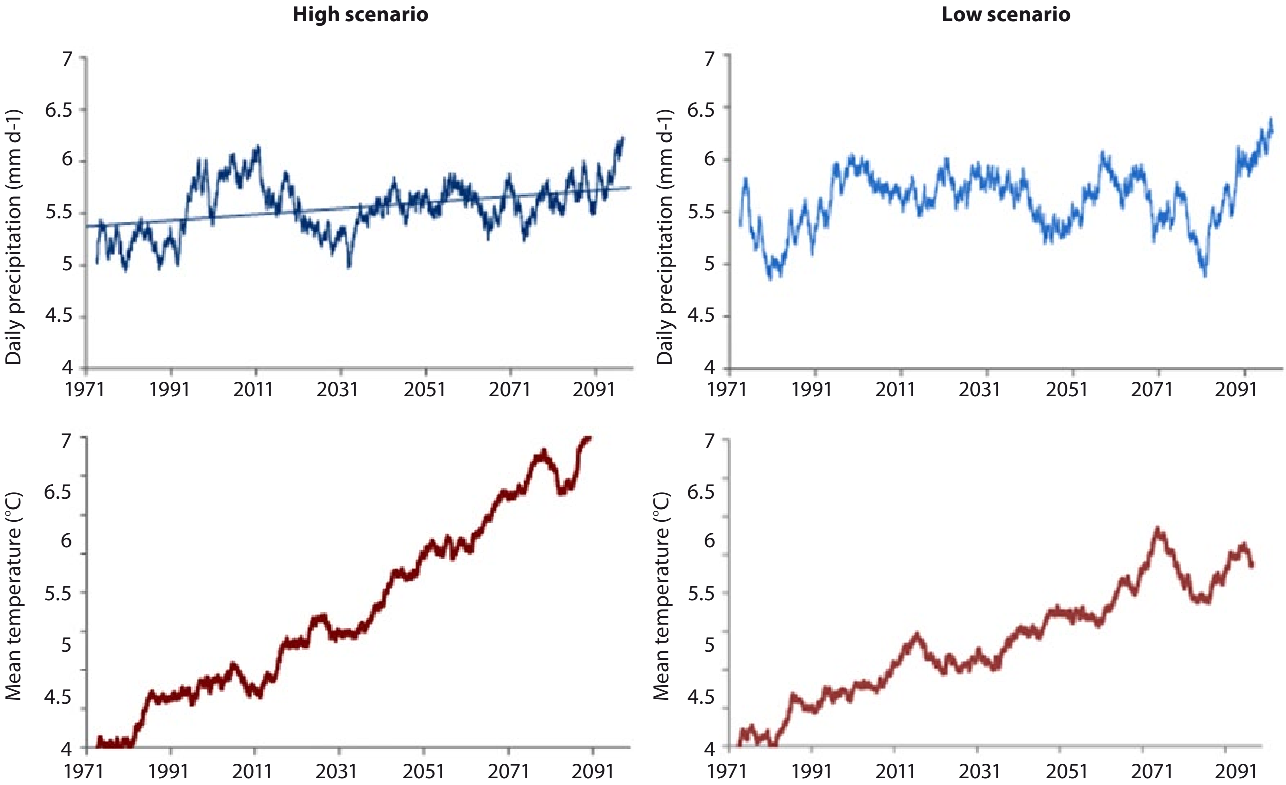


Figure 2.28. Temporal pattern of rainfall and temporal change for the high and low adaptation planning scenarios over period 1971–2091. Straight line in high scenario daily precipitation graph shows the linear trend. Analysis courtesy of Kirchbuam (pers com M. Kirchbuam 2012).

4.4 Interpreting projections

Establishing a range of quantitative scenarios is one way to provide primary sector managers with information around the broad directions of climate change. Another approach is to broaden the depth of scientific evidence; and to establish expert interpretations of the quantitative projections as well as of the foundation theories, observational studies and process science. These are semi-quantitative judgements that also factor in logical estimates of certainty.

Table 2.4 is a good example of this approach to establishing climate change scenarios for New Zealand, originally formed as part of local council guidance material (MFE 2008). It illustrates the main features of climate change projections for New Zealand as a whole, indicating the direction, magnitude of change, and important spatial/ seasonal variations. This includes an assessment of the degree of confidence in the projections and evidence for a broad range of variables. These interpretations form the broad basis of the adaptation reviews in the coming chapters, complementing the quantitative PSAS used in the more targeted model analyses.

The interpretations in Table 2.4 were based on science in 2008, and still provide a broad basis for primary sector professions in New Zealand. But there are a number of important additions that could be made for primary sector managers given recent science

- Droughts are expected to change in frequency in accordance with the two studies described in Sections 4.2.2 and 4.3.1. It is appropriate to assign a 'confident' (Table 2.4) level of certainty to the scenario that droughts could increase in a warming global environment in New Zealand. The 'confident' rather than 'very confident' level is assigned due to the sensitivity of these estimates to evapo-transpiration, and the role of the radiation budget in this process (Clark et al. 2011). The role of clouds in the energy balance, and the uncertainties of climate models to resolve them adequately are described in Box 2.2 as part of the discussion on feedbacks

- More recent studies reported in this chapter build confidence around the attribution of temperature rises in New Zealand to global warming (Dean & Stott 2010) and the likelihood of increases to the intensity of extreme events (Carey-Smith et al. 2010).

Table 2.4. Main features of New Zealand's climate change projections (Source: MFE 2008). The degree of confidence placed by the authors of the source report in the projections is indicated by the number of stars in brackets (see Table notes for legend).

Climate variable	***Direction of change***	***Magnitude of change***	***Spatial and seasonal variation***
Mean temperature	Increase (****)	All-scenario average 0.9°C by 2040, 2.1°C by 2090 (**)	Least warming in spring season (*)
Daily temperature extremes (frosts, hot days)	Fewer cold temperatures and frosts (****), more high temperature episodes (****)	Whole frequency distribution moves right	
Mean rainfall	Varies around country and with season. Increases in annual mean expected for Tasman, West Coast, Otago, Southland and Chathams; decreases in annual mean forNorthland, Auckland, Gisborne and Hawke's Bay (**)	Substantial variation around the country and with season	Tendency to increase in south and west in the winter and spring (**). Tendency to decrease in the western North Island, and increase in Gisborne and Hawke's Bay, in summer and autumn (*)
Extreme rainfall	Heavier and/or more frequent extreme rainfalls (**), especially where mean rainfall increase predicted (***)	No change through to halving of heavy rainfall return period by 2040; no change through to fourfold reduction in return period by 2090 (**)	Increases in heavy rainfall most likely in areas where mean rainfall is projected to increase (***)
Snow	Shortened duration of snow season (***), Rise in snowline (**), Decrease in snowfall events (*)		
Wind (average)	Increase in the annual mean westerly component of windflow across New Zealand (**)	Approximately 10% increase in annual mean westerly component of flow by 2040 and beyond (*)	By 2090, increased mean westerly in winter (>50%) and spring (20%), and decreased westerly in summer and autumn (20%) (*)
Strong winds	Increase in severe wind risk possible (**)	Up to a 10% increase in the strong winds (>10m/s, top 1 percentile) by 2090 (*)	
Storms	More storminess possible, but little information available for New Zealand (*)		
Sea level	Increase(****)	At least 18–59 cm rise (New Zealand average) between 1990 and 2100 (****)	
Storm surge	Assume storm tide elevation will rise at the same rate as mean sea-level rise (**)		

Notes:
**** Very confident, at least a 9 out of 10 chance of being correct. Very confident means that it is very unlikely that these estimates will be substantially revised as scientific knowledge progresses.
*** Confident.
** Moderate confidence, which means it is more likely than not to be correct in terms of indicated direction and approximate magnitude of change.
* Low confidence, but the best estimate possible at resent from the most recent information. Such estimates could be revised considerably in the future.

5 Climate science for adaptation

5.1 *Climate science and adaptation decisions*

Climate impacts are a result of both climate exposure and factors that influence vulnerability. On its own climate science provides knowledge around baseline exposure, but does not provide the full set of information required to estimate impacts or assess adaptations in primary sectors. As shown in the previous sections understanding climate exposure itself is not straightforward, nor is scientific understanding of it complete. The climate system will continue to bring surprises, and there are irreducible uncertainties involved in developing plausible scenarios of what the future may hold. The available science provides some insights into what changes are occurring and what this may mean in the future; and the best guidance will always be a range of plausible alternative futures, not one certain prediction.

Objective climate science has a strong ongoing role to play in future adaptation decisions. Particularly through its influences on decision making confidence and by using updated science to continually challenge decision making heuristics. Information from climate science is one of the many influences on primary sector managers' risk perception of climate variability and change. Ultimately, it is these perceptions that underpin primary sector decisions around weather and climate, including a decision to undertake deliberate adaptation. As described by Stokes & Howden (2010) having a degree of confidence that climate change is a real phenomenon is a necessary condition for adaptations to be implemented.

Just how a range of future climate scenarios can be applied in decision making is an open question. As described by Dessai et al. (2009) there is considerable danger if adaptation decisions are completely dependent on the predictive accuracy of climate models. When placed in a traditional 'optimal solution'-based decision making processes, this approach sets methodologically based limits to adaptation as it hinges on the accuracy of climate predictions. It leads to a situation where tangible actions cannot be taken because of uncertainties. However, in other areas where there are similar irreducible uncertainties such as earthquake risk, national security and public health, decisions are made all the time without the aid of precise prediction.

For climate change adaptation, Dessai et al. (2009) identify the process of 'robust decision making' as the pragmatic way forward, where strategies are developed that work across a range of alternative climate futures. Many primary sector managers do this as a matter of routine when considering how to operate in season-to-season timeframes: a livestock producer considers a seasonal forecast, but has a strategy that works across the full range of potential outcomes for the coming three months. As described in Chapter 1, extending this approach to adaptation is about finding the 'win-win' strategies, or assessing where there is clear evidence of benefits from pursuing a climate change adaptation.

This type of 'what-if' or 'scenario based planning' has been used successfully to prepare for other phenomena where there are uncertainties, in a way that utilises the full suite of available scientific and management knowledge. As described in Chapter 1, adaptive management and continually updating robust decision making provides a constructive way forward with climate change adaptation. This also involves going beyond climate exposure and developing information sets that tackle the full 'impact equation'. Such assessments are the focus of the sector-based chapters that follow. These issues are described in more detail in Chapter 9, where some of the implications for implementing adaptation are discussed.

5.2 *Climate knowledge gaps*

Some key knowledge gaps remain around climate changes in the New Zealand climate system. Rather than identifying a full suite of research initiatives, the focus in this chapter is on identifying some sensible reducible uncertainties in climate science that are of relevance to primary sector managers.

- The land manager must be prepared for surprises that arise within their local context. When understanding of local climate is deemed critical by primary sector operators, but knowledge at this scale is incomplete or based wholly on manager's heuristics, the first step toward building a higher degree of certainty in climate adaptation may be a local monitoring network. In critical areas and 'high-risk-high value' industries, sub-regional to local resolution climate modelling experiments may be warranted to improve risk awareness and improve the accuracy of risk perception.

- Although good steps have been taken through initiatives like RCM and WRF climate modelling, more work on fundamental physical knowledge concerning the behaviour, modelling and downscaling of the precipitation mechanism is warranted. The nature of the 'spill-over' effect, how it changes, and gaining more precise geographic estimates of rainfall change is critical in a primary sector and water resource management context. This type of work is ongoing and long-term efforts are needed to reduce uncertainties.

- There is need for further work on decadal-scale climate variability as it relates to New Zealand and its interactions with both longer term climate change and also shorter run variability. While it is convenient to summarise climate across 20-30 year windows, managers will experience climate change from all these sources of variability. Although research on decadal-scale prediction is at a very early stage, there are opportunities emerging – such as global climate model experiments set up to track decadal signals.

- Although there is merit in improving knowledge over time, new climate knowledge on its own is insufficient to build adaptive responses. Further integration with mainstream impact research and primary production science is warranted. Also warranted, are efforts that initiate interactions and partnership between climate scientists, primary sector specialists, land management professionals and land holders across the primary sectors.

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Chapter 3. Dairy

Adapting dairy farming systems in a changing climatic environment

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