Climate Changes, Impacts and Implications for New Zealand to 2100

Synthesis Report: Overall CCII Project

A four-year MBIE-funded project to consider climatic conditions to 2100 and assessed impacts and implications for New Zealand's environment, economy and society

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CONTENTS

CLIMATE CHANGES, IMPACTS & IMPLICATIONS FOR NEW ZEALAND

Anthropogenic climate change poses critical challenges for New Zealand's environment, economy and society.

The CCII programme undertook targeted research on climatic conditions, impacts and implications for New Zealand up to 2100, through five inter-related Research Aims (RAs):

RA1

Improving climate projections.

RA2

Identifying pressure points, critical steps and potential responses.

RA3

Identifying feedbacks, understanding cumulative impacts & recognising limits.

RA4

Enhancing capacity and increasing coordination to support decision-making.

RA5

Exploring options for New Zealand under different global climates.

SUMMARY

The four-year MBIE-Funded programme "Climate Changes, Impacts and Implications (CCII)" with four Research Aims (RAs), has produced:

1) Research Aim 1: An updated set of improved climate projection data for New Zealand to 2100 based on the latest round of global climate modelling.
2) Research Aim 2: Five case studies exploring the potential impacts and implications of climate change along an elevational gradient: alpine-uplands-lowland-coastal-marine.
3) Research Aim 3: A national integrated assessment of potential climate change impacts and implications using a loosely-coupled human-natural systems model.
4) Research Aim 4: Guidance on how to improve the use and uptake of climate change information in decision-making processes based on data obtained from interviews on the views and needs of over 100 stakeholders. The guidance has directly contributed to work underway in the National Science Challenges.
5) Research Aim 5: A set of six globally-linked but NZ-focused climate-socioeconomic-policy scenarios, which have been compared with and considered alongside other future scenarios developed for energy and transport.

CCII has produced 10 synthesis reports (including this one), nine papers published in or submitted to peer-reviewed journals, and 45 national or international presentations have been given. At the time of publication, a further 16 published papers are anticipated.

Each of the CCII Research Aims synthesis reports contains several "Highlights" (see Section 4), which have also been published on the CCII webpage (http://ccii.org.nz).

INTRODUCTION

Information on the impacts and implications of potential climatic variability and change on New Zealand's natural and managed environment is growing, but still limited (Reisinger et al., 2014). Projections of future distributions of indigenous plants and animals, for example, have been based on static, correlational models using generalised climate scenarios lacking critical biologically relevant information (Beale et al., 2008). Socio-economic predictions have been largely based on narrative approaches to qualitatively-based climate scenarios for the next hundred years.

More so than in many countries, New Zealand's natural and managed ecosystems and natural resources sustain the nation's economy and society (McAlpine and Wotton, 2009). Ecosystem services such as water regulation and provision, soil conservation, and primary production underpin an export economy based on agricultural and marine production (Dymond et al., 2012). Natural ecosystems are also an essential part of New Zealand identity and the image we project to the world (MfE & DoC, 2000; MfE, 2007). That they are under extraordinary pressure from intensified resource use and pests is an increasing concern internally (Green and Clarkson, 2005), and a major consideration with regard to global acceptability of our agricultural products (Green Growth Advisory Group, 2011).

Climate change will interact and most likely intensify those pressures over the next 50 to 100 years (McLachlan et al., 2007). Climate change will also interact with population (Black et al., 2008), globalization (World Economic Forum, 2009; Stern, 2007), intensification of environmental resource use (Cordell et al., 2009), and socio-cultural change (Moore and Smith, 1995; Morton, 2007), impacting the environment in complex ways. Existing pressures will be exacerbated (e.g., invasive species, droughts, flooding, sedimentation) and new pressures generated (e.g., novel environmental conditions, coastal inundation, ocean acidification).

The Climate Changes, Impacts and Implications (CCII) project

In 2012, New Zealand's Ministry of Business, Innovation and Employment (MBIE) called for targeted research proposals to their Environment Portfolio (Climate and Atmosphere priority area) addressing the following key question:

What are the predicted climatic conditions and assessed/ potential impacts and implications of climate variability and trends on New Zealand and its regional biophysical environment, the economy and society, at projected critical temporal steps up to 2100?

The National Institute of Water and Atmospheric Research Ltd (NIWA) and Landcare Research Ltd, in collaboration with seven partners (see next section), submitted a proposal and were awarded the contract (C01X1225), which began on 1 October 2012 and ended on 30 September 2016. The total funding for the project was NZ$7.2m.

CCII had the following vision:

This research will significantly improve our knowledge of climate change impacts combined with other critical threats on natural environments (land, freshwater, marine and their components). Knowledge of feedbacks among ecosystem services and impacts of climate change and other drivers (e.g., land-use change) is also much improved, leading to enhanced understanding of cumulative impacts on natural resources and environmental limits. As a result, policy makers, planners, resources managers, business and iwi have the capacity to better anticipate future trends and uncertainties in ecosystem services. They will act adaptively to manage services with minimal risk, thereby maintaining current services and safeguarding future options. Lastly, New Zealand's businesses that depend on the environment (e.g., primary industries, tourism and energy) accelerate their transition to a "green growth" pathway, thus New Zealand's economy continues to grow while reducing impacts on the environment.

THE APPROACH

CCII structure and philosophy

The CCII project sought to achieve the outcomes in the vision statement by performing research in and producing outputs from the following five integrated research aims (RAs):

RA 1 **Improving climate projections:** Produce new climate change scenario projections for input into impact models;

RA 2 **Identifying pressure points, critical steps and potential responses:** Perform five case studies on the potential impacts of climate change and other key drivers on alpine, hill & high country, lowland, coasts & estuaries, and marine environments;

RA 3 **Identifying feedbacks, understanding cumulative impacts, and recognising limits:** Develop a coupled human-natural systems model for New Zealand to study the interplay among climate change, land-use change, population and economic development, and decision-making across a range of scales;

RA 4 **Enhancing capacity and increasing coordination to support decision-making:** Undertake a multi-stakeholder learning process to identify the drivers of and barriers to decision-making, and develop methods to build adaptive capacity; and

RA 5 **Exploring options for New Zealand under different global climates:** Synthesise the research and embed findings in organisations to support coordinated, evidence-based decision-making.

The overarching methodological philosophy of the project was "integration" and "co-production of knowledge". Figure 1 shows the four-year project plan. The plan highlights the interconnectedness of the five RAs and shows how stakeholders were integral throughout the programme.

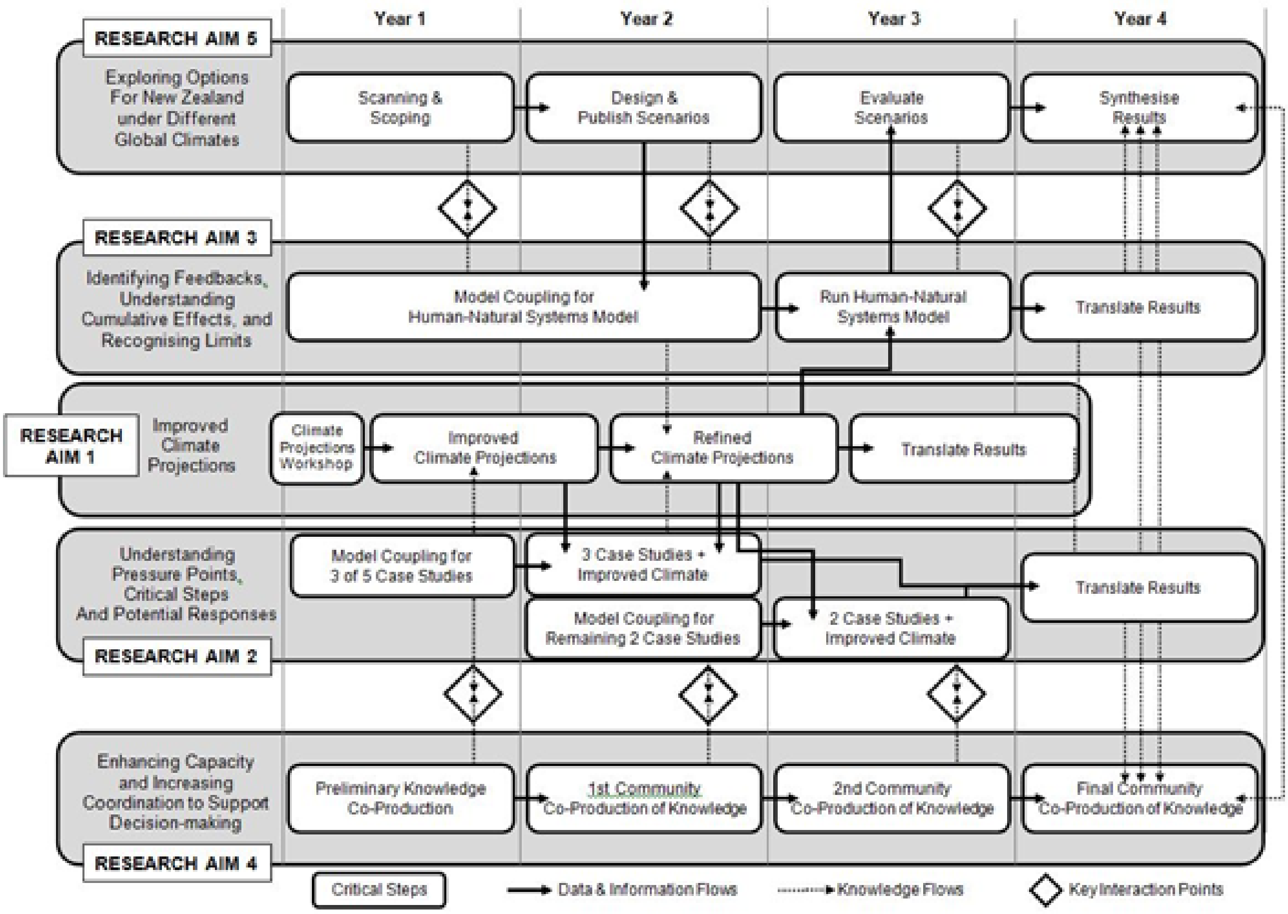

Figure 1: CCII 4-year project plan.

RA 1 was central and generated improved climate projections for New Zealand that flowed throughout the project. RAs 2 and 3 served several roles. They were formal research exercises in modelling pressures, critical steps, cumulative impacts, and limits. They also served as learning environments for both researchers and stakeholders via interactions with Communities of Practice in RAs 4 and 5. RA 2 principally interacted with the three outcome-oriented communities in RA 4. RA 3 principally interacted with RA 5. However, the extensive knowledge networks employed throughout the project maximised the likelihood for information and knowledge transfer and learning, which culminated in the synthesis in RA 5 (top right) and the final community co-production of knowledge in RA 4 (bottom right).

The CCII research team

The project brought together a research team with strong knowledge, substantial experience, and robust modelling capabilities in climate, ecosystems, land and water use, economics, and sociocultural research to address the MBIE Environment sector investment plan priority of "stronger prediction and modelling systems". Team members came from NIWA, LandCare Research, AgResearch, Victoria University of Wellington, Bodeker Scientific, Motu Economic Research, Plant & Food Research, Scion, GNS Science and Waikato University.

The following table lists all the researchers who significantly contributed to CCII. Many others, who contributed but not as significantly, are not listed here.

Table 1: CCII researchers, affiliations and associated research aim. PLT is "project leadership team".

Researcher	Affiliation	Research Aim
Andrew Tait	NIWA	PLT (CCII co-leader & RA1 leader), RA1, RA2 (lowlands)
Daniel Rutledge	Landcare Research	PLT (CCII co-leader and RA3 leader), RA2 (uplands), RA5
Bob Frame	Landcare Research	PLT (RA5 co-leader), RA5
Dave Frame	Victoria University of Wellington	PLT (RA4 co-leader), RA4
Judy Lawrence	PS Consulting Ltd	PLT (RA4 co-leader), RA4
Graham McBride	NIWA	PLT (RA2 co-leader), RA2 (coastal)
Jake Overton	Landcare Research	PLT (RA2 co-leader), RA2 (uplands)
Andy Reisinger	AgResearch Ltd	PLT (RA5 co-leader), RA5
Brett Mullan	NIWA	RA1
Abha Sood	NIWA	RA1
Stephen Stuart	NIWA	RA1
Greg Bodeker	Bodeker Scientific	RA1
Stefanie Kremser	Bodeker Scientific	RA1
Jared Lewis	Bodeker Scientific	RA1
Mandy Barron	Landcare Research	RA2 (alpine)
Roger Pech	Landcare Research	RA2 (alpine)
Jenny Christie	DoC	RA2 (alpine)
Norm Mason	Landcare Research	RA2 (uplands)
Varvara Vetrova	Landcare Research	RA2 (uplands), RA3
Levente Timar	Motu Economic Research	RA2 (uplands and lowlands), RA3
Christian Zammit	NIWA	RA2 (uplands, lowlands and coastal), RA3
Liz Keller	GNS Science	RA2 (uplands and lowlands), RA3
Andrew Dunningham	Scion	RA2 (uplands and lowlands), RA3, RA4
Anne-Gaelle Ausseil	Landcare Research	RA2 (lowlands)
Kerry Bodmin	NIWA	RA2 (lowlands)
Edmar Tiexiera	Plant and Food Research	RA2 (lowlands), RA3
Adam Daigneault	Landcare Research	RA2 (lowlands), RA3, RA5
Scott Stephens	NIWA	RA2 (lowlands and coastal)
Rob Bell	NIWA	RA2 (lowlands and coastal)
Glen Reeve	NIWA	RA2 (coastal)
Andrew Swales	NIWA	RA2 (coastal)
Mark Pritchard	NIWA	RA2 (coastal)
Carolyn Lundquist	NIWA	RA2 (coastal)
Cliff Law	NIWA	RA2 (marine)
Graham Rickard	NIWA	RA2 (coastal)
Sara Mikaloff-Fletcher	NIWA	RA2 (coastal)
Matt Pinkerton	NIWA	RA2 (coastal)
Richard Gorman	NIWA	RA2 (coastal)
Corey Allan	Motu Economic Research	RA3
Daniel Collins	NIWA	RA3
Doug Booker	NIWA	RA3
Michael Cameron	University of Waikato	RA3
Robbie Price	Landcare Research	RA3
Paula Blackett	AgResearch and NIWA	RA4
Nicholas Cradock-Henry	Landcare Research	RA4
Stephen Flood	Victoria University of Wellington	RA4
Alison Greenaway	Landcare Research	RA4
Erika Mackay	NIWA	Synthesis Report designer
Nicky Brookes	Bodeker Scientific	CCII.org.nz website manager

End-users from government, business, iwi, and communities also participated directly in the project through attendance at community of practice workshops, involvement on the governance group, and one-on-one and group interviews.

Figure 2: Group discussion at the CCII coastal case study workshop, 29 September 2016.

Models brought to bear

Primarily, the CCII project employed and adapted a suite of existing models (Table 2) – including environmental, economic, land-use change, and demographic models – to assess the impacts of climate change at both the case study (RA2) and national levels (RA3). Models were, as much as practicable, coupled together to evaluate the scenarios developed in RA5, although this proved very difficult in the main (see "Reflections on the Project", pages 20-21).

The two new models developed for CCII came about due to the necessity to simplify sediment deposition over multiple tidal cycles (coastal case study) and the need for a simple temperature index model for kiwifruit viability (lowlands case study).

Table 2: Models used in the CCII project, including the relevant New Zealand institution with the capability to run and interpret these models.

Model name	Model purpose	Institution with capability
HadGEM2-ES (UK) CESM1-CAM5 (USA) NorESM1-M (Norway)GFDL-CM3 (USA) GISS-E2-R (USA) BCC-CSM1.1 (China)	Global Climate Models	NIWA (as a user of the model outputs)
HadGEM3-RA	Regional Climate Model (RCM) used in combination with the GCMs to generate climate projections for NZ	NIWA
AIM-CGE (Japan) GCAM (USA) IMAGE (The Netherlands) MESSAGE-GLOBIOM (Austria) REMIND-MAGPIE (Germany) WITCH-GLOBIOM (Italy)	Global Integrated Assessment Models	Landcare Research University of Waikato (as uses of model outputs)
EPIC	Ensemble Projections Incorporating Climate model uncertainty	Bodeker Scientific
Delta-T	Temperature-based beech masting	Landcare Research & DoC
Topnet	National hydrological model	NIWA
Biome-BGC	Pasture productivity	GNS Science
LURNZ	Econometric model of national rural land use	Motu Economic Research
CLIMEX	Pest suitability	Scion
WATYIELD	Water yield (related to wilding conifers)	Landcare Research
Fire Weather Index	Wildfire intensity and spread	NIWA and Landcare Research
APSIM	Crop productivity	Plant and Food Research
Temperature index kiwifruit viability model	As described in model name	NIWA
NZFARM	Farm-based net revenue maximisation	Landcare Research
TELEMAC 3-D	River hydrodynamics and saline intrusion	NIWA
Deltares 3-D hydrodynamic and sediment transport model	As described in model name	NIWA
'0-D' water column sedimentation model	As described in model name	NIWA
Earth System Models	Marine SSTs, nutrients, Chlorophyll-a	NIWA
FluxFish	Uses food particle flux with the current spatial distribution of fish species and their diets	NIWA
CliMAT–DGE	Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium model	Landcare Research

SYNTHESIS REPORTS HIGHLIGHTS

RA1 Climate Projections

- Over 35 TB of global climate data were downloaded from the Coupled Model Inter-comparison Project (CMIP-5) data repository from over 40 General Circulation Model (GCM) runs, performed for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5).
- The six best-performing GCMs for the New Zealand region were selected, based on comparisons with observations over the historical data period of the models. These models are: HadGEM2-ES (UK), CESM1-CAM5 (USA), NorESM1-M (Norway), GFDL-CM3 (USA), GISS-E2-R (USA) and BCC-CSM1.1 (China). Each of these models performs better than the 12 CMIP-3 models used previously for New Zealand climate change assessments.
- Sea surface temperature (SST) data from these six GCMs were bias-corrected and, together with a global atmospheric GCM, were used as initial and boundary conditions for the higher spatial resolution (~27km) NIWA Regional Climate Model (RCM). Temperature and precipitation data from the RCM were bias corrected using the Linked empirical Modelled and Observed Distribution (LeMOD) correction method and all climate variables and indices were further downscaled to the ~5km grid of the Virtual Climate Station (VCS) data.
- The Ensemble Projections Incorporating Climate (EPIC) model uncertainty method was developed to generate large ensemble projections of maximum and minimum temperatures at daily resolution for all of New Zealand, out to 2100. These data can be used to generate probability density functions (PDFs) of future maximum and minimum temperature.
- The New Zealand-downscaled GCM and RCM data have been analysed and the results presented in a comprehensive report for the Ministry for the Environment.
- Maps of projected climate changes have been produced for several variables, with the temperature and precipitation maps available for each of the six GCMs and the 6-model-average, via Our Future Climate New Zealand*. The OFCNZ tool also allows users to view time series charts of changes in temperature and precipitation for 15 locations around the country.
- The Future Extremes** web page has also been developed. This tool allows the user to select any location in New Zealand and the variable of interest (hot days, frosts, hot spells or cold spells), the emissions scenario, and whether the results should be shown as probabilities, number of events per year, or number of events per decade.
- The CCII RA1 climate dataset is a landmark dataset that will be used by multiple researchers and stakeholders for many years to come, to produce a consistent baseline of knowledge on climate change impacts and implications for New Zealand.

RA2 Alpine Case Study

- New Zealand's alpine and sub-alpine systems are characterised by plant communities that occasionally produce very large seed crops (masts). Masts result in irruptions of rodents and their predators, primarily stoats, with subsequent severe predation impacts on native fauna. Masts can be predicted using the difference in successive summer temperatures, i.e. the ΔT model (Kelly et al. 2013). Historic, current and projected summer temperature data were used in the ΔT model to predict the timing and extent of masts in forest dominated by beech (Fuscospora spp.).
- Masts are often synchronised over very large areas of beech forest, i.e. at regional scales.
- Mega-masts, i.e. masts occurring over >50% of beech-dominated forest, have occurred 11 times over the last 40 years.
- Virtual Climate Station Network (VCSN) temperature data were used to correctly forecast mega-masts in 2014 and 2016. These forecasts contributed to planning for DOC's high-profile pest control programme, 'Battle for our Birds'.
- Spatially explicit forecasts of masts will help Department of Conservation (DOC) managers identify those areas of high conservation value that coincide with a high probability of a mast and therefore are threatened by a pest irruption in any particular year.

* http://ofcnz.niwa.co.nz
** http://futureextremes.ccii.org.nz

- Climate projections up to 2100 suggest mega-masts, and hence wide-scale pest irruptions, are likely to continue to occur episodically regardless of Representative Concentration Pathway (RCP). This indicates that provision of contingency funds for managing mast-induced irruptions of pests could be based on approaches used for other natural events such as wildfires, floods and earthquakes.
- Differences between General Circulation Models (GCMs) mask any significant differences between RCPs in their predicted effects on the frequency of mega-masts during the 21st century.
- The approach of combining spatial climate projections with a climate-based model for beech masts could be used for predicting the effects of climate change on other masting ecosystems worldwide.
- Actuarial or other risk-management approaches are likely to be required in the future to better manage periodic pest irruptions.

RA2 Uplands Case Study

- The Uplands Case Study undertook loosely-coupled systems modelling to better understand the potential impacts and implications of climate change for the economy, environment and society in the upper Waitaki catchment from an integrated perspective. Systems modelling was used to evaluate scenarios linking global development organised along socioeconomic and representative greenhouse gas concentration pathways with selected aspects of New Zealand development both nationally and sub-nationally, e.g., the upper Waitaki catchment.
- Impacts and implications of climate change in the catchment will result from both direct and indirect effects of a suite of interacting biophysical, socioeconomic and cultural drivers operating across global, national, regional, and local scales.
- The regional climate including the study area is likely to become warmer and wetter, with some shifts in seasonal patterns. The number of hotter days ⩾ 25°C and colder nights ⩽ 0°C is likely to increase and decrease, respectively. Frequency of extreme events such as high rainfall or winds could increase as much as 10 to 15%, depending upon the magnitude of future global greenhouse gas concentrations.
- Global and national socioeconomic developments, such as changing commodity prices, will strongly influence the catchment. In some cases, those developments will outweigh the direct, local effects and impacts of climate change in relation to land use change.
- The warming climate and changing precipitation and weather patterns is likely to increase the availability of suitable area for many weeds and reduce suitable area for some. Changes are very likely to vary over time, with some effects felt earlier than others. The shifting patterns of balance and timing will increase challenges to biodiversity and conservation management by shifting management and control priorities and possible increasing the total pressure exerted by weed species on both native biodiversity and primary production.
- Hydrological modelling shows that water management will likely become more challenging and complex. While mean annual flows in the catchment are likely to undergo small average changes over the coming century, mean seasonal flows will likely show more pronounced changes reflecting changes in weather patterns resulting from climate change. Changes in the seasonal patterns will affect the timing of storage and delivery of water for a range of uses.
- Annual pasture productivity is likely to increase overall due to increased plant growth resulting from the likely increase in precipitation and water availability and CO_2 fertilization effects from higher atmospheric CO_2 concentrations. Large seasonal changes, including summer feed gaps and more productive winters, could necessitate adaptation to shifts in the temporal availability of forage for livestock.
- Although not explicitly modelled, expected trends in climate change will likely have negative implications for tourism and recreation. For example, reduced snowfall and/or the ability to operate snow-making equipment could over time reduce the net number of days suitable for skiing in the catchment. Also, higher frequency of extreme events could increase risks of damage to important tourism infrastructure such as huts and tracks.
- Expansion of the range of wilding conifers would likely increase water yield and help mitigate the increasing wildlife risk from climate change. However, that expansion is very likely to negatively

impact native biodiversity and primary production in complex ways, e.g., further invasion of tussock grasslands would reduce the extent and ecological integrity of native ecosystems and area remaining in primary production.

- In summary, the uplands case study demonstrated that climate change, when considered in conjunction with broader socioeconomic developments, will likely increase uncertainty and risks and therefore increase challenges to policy, business planning, resource management, and societal resilience into the future. The ability to cope and adapt to changing risk profiles varies among scenarios and depends both on assumed socioeconomic developments as well as the expected degree of climate change.

RA2 Lowland Case Study

- In the Bay of Plenty, there will be a likely increase in mean air temperature and number of hot days and dry days, increasing the risk of drought.
- There is likely to be more rain in summer and less in winter and spring.
- Sea level rise will affect the coastal zone around the Kaituna catchment, with 5,500 ha likely to be regularly inundated every couple of weeks during high tide (1.8 m above mean sea level) affecting the dairy industry and maize cropping.
- Change in pasture production is positive under all scenarios for both sheep and dairy pasture. The magnitude of the change is larger for dairy than for sheep. Total annual pasture growth increases by 1–5 % around mid-century and by 2–7.5% by 2100. Seasonal average growth rates show consistent, large increases in winter and spring, as expected under warmer conditions and an extended growing season.
- For forestry, simulations with constant CO_2, there were reductions in productivity of 4–20% for both 2055 and 2085 depending on the Representative Concentration Pathway (RCP) scenario. For simulations with increasing CO_2, growth increased by about 10–15% by 2055. The between-site variability was higher for the simulations with constant CO_2 than for those with increasing CO_2, with standard deviations by 2085 ranging from 3 to 7% for simulations under constant CO_2, which reduced to 2–3% under increasing CO_2. It is consistent with the general tendency for increasing CO_2 to have greater beneficial effects for plants growing under otherwise more stressful conditions.
- For maize silage, the impact of climate change yields was assessed considering model runs with or without adaptation of crop genotype and sowing dates. Model results indicate a higher risk of yield losses when sowing dates are not adapted. For these conditions, yield loss estimates increase from mid-century (5%) to the end of the century (12%). In contrast, by adapting sowing dates to a warmer climate (i.e. sowing early), yield losses were minimised and yield gains occurred for specific locations. Climate change impacts on silage yield were uneven across the catchment. More negative impacts were estimated in the northern lowlands, currently the most suitable area for arable cropping.
- Hayward kiwifruit production viability for the Te Puke area is projected to decrease steadily over time and becomes consistently marginal by the 2050s and non-viable by the end of the century. The key reason for this is the loss of sufficient winter chilling as the climate warms. However, other inland North Island regions and many parts of the South Island (particularly Canterbury) show an increase in viability (based purely on temperature) for this crop variety over the century.
- Land-use change in the catchment could be significant over the next century, and is projected to be affected by both the socioeconomic pathways and climate change. The Shared Socio-Economic Pathway scenario chosen (SSP3) is projecting high log and sheep & beef prices compared with dairy prices. By comparing two land-use change models, we found that there is generally a shift from sheep & beef farming to forestry by the end of the century. High log prices cause forestry to increase beyond baseline levels in both models. However, discrepancies in model assumptions and structure meant that there were differences in dairy changes (opposite directions) and magnitude. Regardless, the consistent result of an increase in afforestation in the Kaituna by 2100 across all scenarios suggests environmental outputs such as GHG emissions and freshwater contaminant loads could be reduced over the next century, even if there is some intensification in the catchment.
- For the remaining swamps in the Kaituna, increased precipitation may induce a change in wetland type to a permanently wet state (e.g. ephemeral to swamp); a higher nutrient system (e.g. fen to swamp), or a

more aquatic system (shallow water, pond or lake). Lower rainfall would increase pressure on obligate wetland plants and therefore vegetation types dominated by these species. Changes in rainfall periodicity or intensity will also have an impact, as it may increase the extent of wetland margins and thus favour facultative dryland species, many of which are alien weeds.

- An integrated assessment provided an overview of potential future impacts of both climate change and socio-economic changes. In the scenario that was investigated (high Representative Concentration Pathways (RCP), fragmented world), there is almost no attempt to curtail climate change on a global scale and only very limited, reactive local efforts. Costs of production would generally increase due to a need for increased environmental management for pest control and water shortages, with a higher risk for a decline in commodity prices due to increased global competition.

RA2 Coastal Case Study

Firth of Thames water levels and depths

- Sea level rise (SLR) will result in increased flooding of shore communities.
- Water depths in the Firth over time are projected to be relatively independent of RCP values (with rate of sea level rise roughly in tandem with sedimentation), but will nevertheless be maximal for RCP 8.5 (high greenhouse gas emissions).
- Areas of wetting and drying in the Firth may increase over time, particularly if more intense land uses evolve, making navigation more difficult.
- Conversely, there would be less wetting and drying were widespread reforestation to be adopted in the contributing catchments.

Firth of Thames mangrove distributions projections

- Under present landuses, up to 100% increase in mangrove habitat is projected in suitable areas, with a decrease of habitat in subtidal areas.
- For a 20% reduction in sediment supply (e.g., because of reforestation) some reduction in suitable habitat can be expected, especially for areas presently marginal for mangrove production.
- For a 20% increase in sediment supply (e.g., because of intensified landuses) a general increase in suitable habitat is projected.

Waihou and Piako River flows

- Projected changes in river flows are strongly linked to projected changes in precipitation.
- The median change in the annual mean flow is relatively small, with generally negative changes in winter and summer (decreased mean flow) and positive changes in spring and autumn (increased mean flow).
- Uncertainty in flow projections is high, corresponding to similar uncertainty in future precipitation projections for this region.

Waihou River salinity intrusion and flooding

- SLR is the main contributor to changes in saline intrusion and flooding.
- Salinity intrusion up the Waihou River is projected to extend up to a further 5 km inland (for a 1 metre SLR over the next century), and is relatively unaffected by changes in low river flows.
- Flooding in the upper part of the river (>50 km from the Firth) is largely unaffected by SLR.
- The largest impact of SLR and flood interaction will occur in the lower Waihou River (between Pekapeka and Puke Bridge), with up to a 0.5 m increase in combined flood level at Pekapeka for a 1 m SLR.

Economic and land use scenario analysis

- Agricultural commodity prices vary significantly over time due to changes in global socio-economic conditions, population growth, and climate change policy.
- Primary production is estimated to increase regardless of which Representative Concentration Pathway (RCP) is modelled. Forestry yields increase the most due to the influence of an increase in atmospheric CO_2.
- A scenario of increased sediment loads is driven by deforestation and a shift to pastoral land uses.
- A scenario of a decline in sediment loads can be attributed to high carbon prices shifting marginal sheep and beef land to pine plantations, scrub, and fallow land.

RA2 Marine Case Study

- Most of the ocean properties assessed are highly sensitive to future CO_2 emissions, with the high emission scenario (RCP8.5) yielding the largest projected changes.

- Mean sea surface temperature will increase by 2.5°C, and exceed 3°C in the north Tasman Sea. Decreases in surface chlorophyll-a, nitrate, phosphate and pH accompanied by shallowing of the surface layer.
- Projected changes in wave height are relatively small, with the largest increases (<+4%) in Subantarctic waters south of NZ, and decreases (-5%) on the Chatham Rise Region.
- Surface water nutrient concentrations will decline, particularly in the eastern Chatham Rise region, with a decrease in nitrate by ~9% under RCP8.5. Conversely dissolved iron is projected to increase Subtropical water.
- The pH of surface water will decline by 0.33 under RCP8.5, with the resulting pH (7.77), and associated rate of change in pH, being unprecedented in the last 25 million years. Subantarctic surface pH will fall below the current pH minimum around 2030, with acidification creating corrosive conditions for organisms with carbonate shells in Subantarctic surface waters.
- Primary Production in surface waters will decline by an average 6% from the present day under RCP8.5, with Subtropical waters, experiencing the largest decline.
- The decrease in particle flux from the surface to the seabed, of 9-12% by 2100, indicates that carbon sequestration will decline in the open ocean around New Zealand.
- Changes in particle flux will alter the food available for fish. A decline in particle flux was identified for all 38 species (including 30 commercial species), ranging from 2.2 to 24.6% by 2100. The largest decline in particle flux occurs in areas occupied by the northern spiny dogfish, gemfish, frostfish and tarakihi, and lowest decline in areas occupied by black oreo, barracouta, southern blue whiting and blue warehou.
- Climate change will not significantly lower dissolved oxygen in the mid-water around NZ, but the depth at which carbonate dissolves will become progressively more shallow. This will contribute to a decline in suitable habitat for cold water corals in New Zealand waters, and impact deep-sea ecosystems and biodiversity. The Chatham Rise may provide temporary refugia, which should be considered in spatial management of marine protected areas.
- The regional variation of the impact of climatic change in New Zealand waters needs to be considered in management and policy decisions. For example, regions that are most sensitive to climate change include Subantarctic waters south of 50oS and the eastern Chatham Rise, which support important fisheries, and Subtropical waters north-east of NZ.

RA3 National Integrated Assessment

- Research Aim 3 (RA3) undertook a national integrated assessment that explored the impacts and implications of climate change to 2100 to better understand feedbacks, cumulative impacts, and limits among economic, social, and environmental outcomes.
- The assessment evaluated six globally-linked, New Zealand-focused scenarios using a loosely coupled national human-natural systems model developed for RA3. The systems model integrated a suite of climate, economic, land use, hydrology, and primary production models.
- The six CCII scenarios were a subset of 20 global scenarios formulated under a new global scenario architecture developed for the IPCC's 5th assessment.
- Global scenarios combine 1) socioeconomic pathways exploring different levels of challenges to mitigation and adaptation, 2) greenhouse gas concentration pathways, and 3) shared policy assumptions about global efforts to mitigate greenhouse gas emissions.
- By design, socioeconomic pathways evolve independently of greenhouse gas concentration pathways. Any pair of pathways can be combined to form a scenario. As a result, climate change does not directly impact socioeconomic development. Instead, evaluation of climate change impacts and implications occurs indirectly by comparing and contrasting different scenarios.
- A global integrated assessment study found that any global scenario is plausible but not all are equally feasible. Feasibility decreased when pairing socioeconomic pathways with high challenges to mitigation and the lowest concentration pathway.
- Any global scenario with a mitigation target assumes a functional global carbon market, although that assumption is not equally plausible across all mitigation scenarios.

- RA3 modelling followed global integrated assessment study protocols. Scenario evaluation specified that country-level population and GDP followed fixed projections unique to the selected global socioeconomic pathway and that all climate-related modelling use climate projections based on the selected concentration pathway.
- CCII scenarios also implemented relevant global shared policy assumptions as required e.g., non-mitigation scenarios assumed no carbon market or carbon price while mitigation scenarios modelled a functional carbon market following global study protocols.
- Improved climate projections for New Zealand reinforce earlier findings that higher greenhouse gas concentrations leading to increasing radiative forcing will likely cause larger degrees of change for New Zealand's climate and its various facets, including means, extremes, frequencies, and shifts in patterns.
- Uncertainty, risks, and vulnerabilities resulting from climate change will also likely scale with increasing concentration pathways. Different locations will experience different impacts depending upon combined changes to daily, seasonal and annual weather patterns.
- Hydrological systems will change both positively and negatively with climate change. Total variability tends to increase with increasing concentration pathways such that low flows become smaller and occur earlier and high flows (i.e. flooding) become larger. Mean flows show more complex spatial patterns but tend to increase in a west-to-east direction.
- Across scenarios, summer soil moisture deficits intensify such that soils become drier except in a few areas of the South Island.
- The lack of links between hydrological and primary production modelling is a key limitation of the current national systems model and corresponding analysis.
- Climate impacts on primary production varied. Pastoral and forestry (*Pinus radiata*) yields to 2100 increased positively with increasing concentration pathway because positive effects from CO_2 fertilisation outweighed negative effects of higher temperatures.
- Sheep & beef and dairy mean annual pasture productivity increased 1-10% across scenarios in most locations, although changes in seasonal trends might cause larger summer feed gaps.
- Irrigated maize silage modelling demonstrated potential for adaptation for minimising impacts on national maize yields. Nationally, cropping could shift from northern regions showing decreasing yields to southern regions showing increasing yields. Locally, farming could adopt new agronomic practices such as earlier sowing dates and long-cycle genotypes.
- A novel modelling experiment demonstrated the use of new climate projection ensembles to better characterise and quantify uncertainty. The model developed statistical methods that quantified potential changes to habitat suitability for whitebait (banded kōkopu juveniles).
- New Zealand's fixed population projections started at 4.4 million in 2010 and ranged by 2100 from 3.8 (low) to 9.8 (high) million people. The large variability in final population has implications related to and independent of climate change including land use change, food security, energy security, water resources, conservation, etc.
- Demographic modelling found that climate change will cause regional populations to shift north slightly and the magnitude of the shift increases with increasing concentration pathways. For example, under the same socioeconomic pathway, Auckland's population at 2100 was ~30,000 higher under a high concentration pathway than a low concentration pathway.
- New Zealand's fixed GDP projections started at $66,813 billion US2005 in 2010 and ranged by 2100 from $277,733 (low) to $1,014,793 (high) billion. New Zealand's GDP per capita begins and always remains higher than the global average for all global socioeconomic pathways. That result suggests that New Zealand remains relatively better off on a global basis although the difference increases or decreases depending upon socioeconomic pathway assumptions.
- Agricultural economic and land-use change modelling showed that changes to productivity via climate change will interact with market forces (e.g., price mechanisms) to drive land use change in complex ways. For example, in one scenario projected global sheep and beef commodity prices went well beyond historic observed ranges and counterbalanced dairy farming expansion that

would occur assuming only climate change effects.

- Given global scenario architecture design and assumptions, broad social and economic outcomes for New Zealand, as indicated by population and GDP, depend primarily on the global socioeconomic pathway selected, whereas environmental outcomes reflect a more balanced combination of socioeconomic pathways and concentration pathways.
- Climate change does substantially impact the specific nature of social and economic outcomes. Comparing two scenarios with the same global socioeconomic pathway but a higher and lower concentration pathway, the structure of New Zealand's economy changed substantially. In the high concentration scenario, the economy became more inwardly focused and dominated by domestic household consumption. In the lower concentration scenario, the economy became more outwardly focused and dominated by exports.

RA4 Decision-Making

- This report presents evidence about the impacts and implications of climate change that have decision relevance for a range of stakeholders. Collaborative and participatory research methods were used to engage with a wide range of stakeholders to better understand the decision landscape affected by climate change impacts and implications. The evidence supports the development of new practices for addressing and planning for climate change impacts and implications in New Zealand. The relationships developed will enable a strategy to be built in order for adaptation practice to mature, and to develop a shared understanding of climate change impacts and implications across public, private, and influential actors and agencies.

Understanding and information

- Perceptions of climate change are dominated by short-term thinking in all but a few sectors, and on 'familiar' risks. The interaction between climate change and other risks, however, will require new strategic approaches to risk management and a greater emphasis on dynamic and emerging risk profiles. More information is required to support the adaptation decisions of stakeholders in dynamic social and economic contexts that will be affected by climate change.
- Information needs and knowledge gaps include understanding future risks for a range of decision-relevant variables; climate change implications for a greater range of stakeholder interests and information to support adaptation decision-making in dynamic social and economic contexts.

Effects

- Climate change will have direct impacts on primary economic activities and have indirect implications for a range of sectors including hydro-electric generation, tourism, commercial forestry and agriculture. Implications are particularly acute for urban areas facing the combined effects of rainfall extremes and sea-level rise, to which legacy infrastructure may be ill-suited. Climate change will create dynamic risk profiles, demanding a more strategic management approach. However, with a few notable exceptions, the private sector has done little to consider changing climate risks on business operations, and serious questions about public and private adaptive capacity remain unanswered.
- Climate change will also create cascades of implications, resulting in a chain of events affecting multiple system domains, including governance. Rainfall extremes can disrupt productive land uses, affecting quality and yield, with implications for transport networks, port access, trade, and economic exchange. Increased irrigation and shifts in land use in response to a drier climate, may result in pastoral farmers moving stock to steeper country, increasing runoff and erosion, with downstream water quality impacts. Such cascading impacts are identified.
- There are functional linkages between land and water management, energy, and climate change that are often treated separately. Inter-basin water transfers and ground water pumping, for example, are energy intensive. Promoting them as a drought mitigation solution or to boost productivity may have implications for sustainability. Such 'nexus' issues also have social consequences. Urban and rural populations may place different values on freshwater than productive sectors, leading to growing tensions over managing this resource. Nexus issues have received only limited attention to date; the integrated tools and solutions required to guide decision making are, therefore, lacking.

Decision-making implications

- Current tools are ill-suited for addressing the uncertainty and long decision time frames posed by climate change. There are dependencies between public and private sectors that are not commensurate with the strategic and inter-generational view that is required. This includes the 'legacy effects' of past decisions, changing risk profiles, regulatory frameworks and functional mandates that emphasise reactive and short-term decision cycles.
- Governance – regulation, coordination and control to enable or constrain action and actors – is fragmented across scales, and between and within organisations, impeding adaptation efforts. There is early evidence of linked-up thinking in regional and territorial councils that developed over the course of the research, but coherent national objectives for climate change impacts throughout New Zealand are vital. Institutional tools to support dynamic adaptive planning, and address economic and fiscal risks, are also needed.
- Organisational capability falls along a spectrum, depending on size, focus, and degree of functional integration within agencies, and across governance levels. Capability and capacity to address climate change impacts and implications depend on management processes, self-efficacy, and resource mobilisation. Access to resources varies widely. Where skills and resources are available in-house, intra-organisational silos may limit the ability to address climate risks. The immediate focus of smaller councils and businesses limits the ability to address climate risk and make connections with other scales or sectors. Most risk management processes and practices are linked to specific issues; for example, fire risk or experienced risks, rather than to changing climate risk profiles.

Engaging with climate change in decision making

- Governance, policy, uncertainty, resources, and psychosocial factors are the greatest impediments to more effective decision-making relating to climate impacts and implications. Mismatch of time horizons for adaptation decisions and political and management practices are the most significant governance barriers, while scepticism regarding the drivers and effects of climate change has, until recently, hampered strategic thinking. Meeting urgent information needs – including climate change guidance, improved monitoring and evaluation, and vulnerability and its drivers – can help support strategic adaptation planning efforts and avoid maladaptive responses.
- Greater integration across governance levels and between societal actors is urgently needed. Opportunities to incorporate greater consideration of climate change impacts and implications into decision making are available, but have not been fully realised. Enhancing the linkages between statutory instruments, and identifying synergies between policy reviews and legislative reform, for example, can provide critical leverage points to help motivate change.
- Tools and policy measures for decision making under conditions of uncertainty and change need to be deployed. Local government urgently needs to build decision capability and capacity, including enhanced networks, access to tailored and state-of-the-art climate information, and national measures to support climate change adaptation. NGOs and communities have a critical place in catalysing change by raising awareness.

RA5 Scenarios

- A socio-economic scenario architecture to 2100 has been produced that links global, national and local modelling of climate change and its impacts and implications with a range of key quantitative and qualitative indicators.
- This combines various feasible global responses to climate change with national climate policy and non-climate policy dimensions.
- We observe that development of meaningful scenarios must:
    - Enable understanding about the extent to which global, national and local-scale societal developments can influence the nature and severity of climate change risks.
    - Involve researchers across many disciplines; stakeholders with an interest in long-term impacts and implications; and policy-makers who take the long-view.
    - Be credible, salient and legitimate but not necessarily downscaled from global models.
- Shared Socioeconomic Pathways (SSPs) describe future global socioeconomic conditions including emissions of greenhouse gases (GHGs). They

outline plausible alternative states of human and natural societies at a macro scale including both narrative and quantitative elements of socio-ecological systems such as demographic, political, social, cultural, institutional, lifestyle, economic and technological variables and trends. They also include the human impacts on ecosystems and ecosystem services such as air and water quality and biodiversity.

- The global SSPs are defined for global scales and lack the detail critical for understanding climate change risks at national and local scales. In RA5 we describe development of national-scale socio-economic scenarios for New Zealand, nested within SSPs, to inform national and local-scale studies of climate change impacts and implications.
- Shared climate Policy Assumptions (SPAs) describe potential climate change mitigation and/or adaptation policies specific to New Zealand, which enable New Zealand-specific futures to diverge from (accelerate, slow down or even counteract) the trends that are assumed in global-scale SSPs. The SPAs capture key climate policy dimensions not specified in the SSPs and provide a means to employ common assumptions across studies. Shared-climate Policy Assumptions for New Zealand (SPANZ) were developed to illustrate how approaches to both mitigation and to adaptation will impact the future (Table 1 on page 9 of the full report).
- We discuss the challenges that result from these choices in the development of national-scale socioeconomic scenarios for impacts; adaptation and vulnerability research, and demonstrate their utility and limitations in a local-scale case study (Table 2 on page 11 of the full report).
- A set of quantitative and qualitative indicators have been identified for each scenario with sources from the project and more widely (Table 3 on page 15 of the full report).

REFLECTIONS ON THE PROJECT

In the CCII project, as might be expected, some aspects worked well and some aspects did not work so well, thus compounding the already substantial challenges that the project team undertook. Below we outline what worked well, what did not work so well and then suggest future developments that would help remediate those aspects that did not work so well and would further enhance New Zealand's shared capability to understand, anticipate, and adapt to the potential impacts and implications of climate change.

What worked well?

- Perhaps most importantly: as evidenced by the key question outlined earlier, New Zealand's stakeholder community recognised and supported the need to improve our collective capacity to understand the potential impacts and implications of climate change in a holistic fashion. CCII only came about because they asked that key question.
- We enjoyed strong support, enthusiastic participation and sound advice from our Advisory Group, communities of practice, stakeholder research partners and broader spheres of engagement.
- We tried to consider the 'Big Picture' and integrate across economic, environmental and social domains, questions, and impacts and took a systems-based approach to provide a truly integrated assessment of climate change implications.
- Unlike global research teams involved in climate and integrated assessment modelling that can have decades of coordinated development and experience, the CCII team came together for the first time. Despite the newness of the team, and the diversity of experience and disciplines represented – which we considered a strength and not a weakness – the team shared a desire to succeed and learn from and teach one another. That shared desire contributed substantially to the overall success of the project in the face of significant challenges.
- We substantially leveraged New Zealand's research investment by re-using, enhancing, adapting and coupling, often for the first time, a broad suite of New Zealand-based models.
- The NIWA regional climate modelling team made significant advances in producing improved climate projections for New Zealand including developing new methods to overcome some persistent biases produced by global climate modelling and improving collaborations with the New Zealand climate data user community to better understand their climate data needs. For example, hydrological modelling revealed some data quality issues that were in turn fed back to the climate modelling team to correct.
- The improved climate projections represent a step-change in quality, relevance and utility including providing future climate data at a daily temporal resolution.
- We developed some novel methods to improve exploration and characterisation of uncertainty through generation of climate modelling ensembles and applying those new ensemble data sets to improve understanding of uncertainty in impact modelling.
- We substantially improved our ability to uptake and apply global climate science knowledge and data to New Zealand, including substantially reducing the "lag" time between availability and application. Those improvements were across the board and included regional climate modelling based on the latest global climate modelling, uptake and application of results from a recent global integrated assessment study, and leveraging and adapting a newly developed global scenario framework for New Zealand purposes.
- We increased our collective capacity to undertake integrated assessments across a range of scales, themes, and questions including for the first time in the New Zealand context making strong links between socioeconomic and biophysical developments across a range of scales.
- A substantial number of existing models employed in RA2 and RA3 underwent significant enhancements and adaptations to help meet project goals and objectives that will benefit future climate change research across New Zealand.
- The New Zealand scenarios framework has the potential to change the perception of how people consider 'futures' and the relationship between socioeconomic developments and drivers and climate change.

- We made significant strides in understanding how decision-making does and, more importantly, does not make use of climate change science and developed guidance to overcome some of the barriers identified.
- In the end, many "disappointments" shared by the CCII research team reflected a desire to have done more. We take it as a very good sign that after all the trials and tribulations experienced, team members still wanted to push ahead.

What did not work so well?

- We proposed the formation of a national Future Studies Group composed of the RA5 research team and interested stakeholders to co-develop and test the New Zealand scenarios framework and resulting scenarios. However we did not form the group due to insufficient interest.
- The significant challenges encountered by the climate modelling team substantially delayed availability of climate data for use by the broader CCII team. The resulting delay significantly reduced the scope of the impact modelling and limited broader interaction and discussion of the improved climate projections and their implications with stakeholders.
- The scenarios developed for New Zealand lacked detail in many areas, which reflected a number of limitations across a range of scales including globally.
- A number of conceptual, methodological, and technical hurdles limited our ability to undertake integrated assessment and undertake systems-based modelling. Examples included challenges in interpreting qualitative data and assumptions in quantitative modelling, the diverse and sometimes incompatible range of computing platforms used by different models, and scale differences (spatial and/or temporal) among different models.
- We encountered significant technical problems combining the climate projection data with the hydrological model. This led to many delays and meant that the hydrological data could not be integrated into other impact models.

What needs to be developed further?

- Most importantly, New Zealand needs a coordinated national strategy for climate change research that defines a roadmap for further developing and integrating the necessary components to enhance the understanding of climate change impacts and implications most broadly. As a short-term objective, the roadmap can outline the key priorities and steps needed to prepare New Zealand to participate in and take advantage of the next round of global climate change assessment, e.g., the IPCC's 6th assessment in 3-5 years' time.
- Reduction or, ideally, elimination of any persistent biases in climate modelling for New Zealand. The development of the New Zealand Earth Systems Model as part of The Deep South National Science Challenge represents an important first step and should yield improvements needed to reduce or eliminate biases given its focus on improving representation of Southern Ocean and Antarctic influences on New Zealand's regional climate.
- Easily and reliable availability of all climate change impacts and implications knowledge and data for maximum use and uptake.
- A stable, long-term climate change impact and implications research team, similar to the global teams that produce the essential knowledge and data need for New Zealand analyses.
- From a scenarios perspective, a coordinated approach to scenario development and application that reduces duplication of effort and improves comparability and compatibility throughout New Zealand.
- Development of a New Zealand integrated assessment research community that can collectively address the various challenges in undertaking integrated assessment research.

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