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Implications of Climate Change for the Construction Sector: Houses

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Preface

This is the first of a series of reports prepared during research into the implications of climate change for the construction sector. This report deals with climate change impacts on houses. A further report dealing with impacts on office buildings will follow.

Acknowledgments

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Note

The first part of this report, containing summaries of impacts, is intended for all readers. The second part, containing detailed analyses of climate change impacts, is intended (in the most part) for non-specialists. The third part, containing detailed climate change scenarios, is intended for those with some knowledge of meteorology and climatology. These climate change scenarios were up-to-date in mid 1999, but are subject to change, which may alter some of the research results.

IMPLICATIONS OF CLIMATE CHANGE FOR THE CONSTRUCTION SECTOR: HOUSES

BRANZ Study Report SR 94
M. J. Camilleri

REFERENCE

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ABSTRACT

The built environment will be affected by climate change in many ways: the purpose of this research was to identify how, and (where possible) how much.

Climate change research has so far concentrated on climate models, measurements of climate variables, and research underpinning impact and adaptation assessments (often focusing on biological systems). Until now, the building industry and the built environment have not been the subject of detailed, quantitative research, and this was recognised as a significant gap by the National Science Strategy Committee for Climate Change.

This research is the first step towards filling that gap for one New Zealand building type – houses. Climate change factors affecting houses are identified, and quantified where possible, by considering current climate change scenarios and building performance.

Major impacts on houses which have been quantified include: substantial reductions in space heating; modest reductions in hot water heating; increases in the number of days of summer overheating per year (e.g. up to about 30-80 for Auckland and Christchurch); decreases of 1-4 times in a flooding return period and increases in building damage from flooding of up to 10 times in extreme cases.

Impacts that could not be quantified include: wind damage, damage from tropical cyclones, and the effects of changes in UV radiation.

A trend to an increased incidence of rare climatic events (e.g. flooding, extreme wind) may be difficult to detect at the time. Confirmation that a change has in fact occurred may take decades.

The impacts of climate change on housing are prioritised according to how likely they are, and how significant the impacts may be. Prioritising in this way highlights the need for future research in some areas, particularly the effect of climate change on the incidence of tropical cyclones and flooding. The most important and urgent impacts requiring action to mitigate or adapt to the likely effects of climate change are flooding (which should be addressed on a regional basis) and house overheating, particularly in regions with already hot summers like Auckland, Northland, and Canterbury.

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1. INTRODUCTION

The Earth's climate is in a constant state of change. Some of these changes take place over millions of years, such as the slow passage from ice-age to ice-age. Others like the Little Ice Age from the mid 16th to mid 19th century, and the short-lived North American dust bowl in the 1930's, take place over a much shorter time (Briggs and Smithson, 1985). In the last few decades it has become apparent that human activities can have an effect on climate (IPCC, 1996). The rapid warming since the 1980's culminating in the hottest six months worldwide on record in 1998, has fuelled fears and debate that human induced emissions of carbon dioxide and other so-called Greenhouse Gases (GHG) are warming the global climate in an uncontrolled and potentially catastrophic way (The Dominion, July 16, 1998). International agreements are now being forged in an attempt to control GHG emissions and limit the long-term, human induced warming under the United Nations Framework Convention on Climate Change[i].

Buildings are constructed to shelter people from the worst effects of weather and climate, mainly uncomfortably hot or cold temperatures, wind and precipitation. At this they are astoundingly successful, even without modern technology, evidenced by the range of human habitation from the Arctic to Antarctic zones.

As the climate changes there is a danger that current building designs will not be suitable for the new climate. However it is likely that the effects would have to be rapid and severe to require substantial modification of existing buildings.

Some research on buildings relevant to climate change in New Zealand has already been undertaken. A series of reports compiled by the Ministry for the Environment (1990) explored the possible effects of climate change on New Zealand, and played a large part in establishing subsequent research programmes, many of which required inter-disciplinary collaboration between previously separate research establishments and groups. These original impact assessments covered almost every aspect of New Zealand society, including a comprehensive section on housing by Johnson (1990). While most of the housing impact statements were qualitative in nature, and were based on climate change scenarios that have now been superseded, more recent research has focused on some of the most critical impacts identified.

Minnery and Smith (1996) state that "for urban areas the most significant climatic impacts are likely to result from an increased frequency of extreme events, including flooding". This view is consistent with that of the Ministry for the Environment (1990) although they note that major uncertainties remain. Assessing the likely impact of changes in flooding has been hampered by the crude flooding scenarios currently available. Based on these, some areas in Australia have been identified as being at risk of potentially huge increases in flooding damage with climate change as flood return periods decrease (Minnery and Smith, 1996). Some regional authorities in Australia and New Zealand are taking steps to include these possible risks in long-term plans[ii].

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[i] See their website www.unfccc.org for programme overviews and summary statements.

[ii] The Hutt Valley Flood Management Plan includes a management strategy which will "… make long-term provisions to raise stopbanks to cope with possible increased frequency of flooding which may result from climatic changes." Wellington, page 88. The Heathcote River Floodplain Management Strategy, prepared jointly by the Christchurch City council and Canterbury Regional Council recognises the impact of ongoing sea level rise and allows for this in modelling potential floods.

Some international research has quantified the GHG emissions of buildings in the current climate, both during construction and occupancy. The construction figures are broadly comparable to figures for New Zealand houses derived by Honey and Buchanan (1992), though the New Zealand data used are now dated. The embodied energy information for New Zealand building materials has been updated under contract to BRANZ by Victoria University, and only limited information on GHG emission figures is available, so up-to-date evaluation of the construction GHG emissions of New Zealand buildings is still some way off.

Until recently, most international research on climate change and buildings has focused on the GHG emissions of buildings, and often only as part of a wider Life Cycle Assessment (LCA) study. Studies are now underway that go beyond qualitative discussion documents. For example, the UK Building Regulations are being reviewed in light of the climate change scenarios to see what amendments are needed (Cole, 1998).

This report is in three parts: the first part (Sections 1-5) provides a general summary covering the impacts of climate change on houses; the next part (Sections 6-17) includes in-depth analyses of each of these impacts; and the final part (Section 18) gives the detailed climate change scenarios on which the analyses were based.

The impacts reviewed are prioritised according to how likely they are to eventuate according to the best available climate science, and then how likely they are to have significant (negative or positive) impacts on houses. The effects of climate change on buildings are many and diverse, and prioritising in this way may assist in the development of sensible strategies for research and mitigation.

2. SUMMARY OF POSSIBLE IMPACTS OF CLIMATE CHANGE IN NEW ZEALAND

Anticipated climate changes are: increased average temperatures; increased extreme summer temperatures; increased rainfall amounts and intensity over most of New Zealand; increases in flooding; and rising sea levels. Changes in tropical cyclones, the El Nino and La Nina weather patterns, wind, sunshine, and cloudiness could occur but the drivers for these changes are not yet understood fully.

Detailed climate change scenarios are given in Section 18, page 88. These scenarios were developed by NIWA for the years 2030 and 2070. These years are commonly used in climate change research, since the year 2070 corresponds to the anticipated doubling of pre-industrial CO_2 levels (even with the internationally agreed reductions in annual CO_2 emissions), and 2030 is about halfway to 2070. Houses being built now are expected by the New Zealand Building Code to have a 50-year durability, and the lifetime of New Zealand houses is longer than this, so many should still be habitable between 2030 and 2070.

The scenarios are expressed as the ‘low’ and ‘high’ end of a range of possible results. This range is not to be interpreted as some kind of ‘standard deviation’, but merely reflects the large uncertainties in the models about how much Greenhouse Gas (GHG) will be emitted in the 21st century, physical factors, and the behaviour of the Earth’s climate. Given the current state of climate change science, the high end of the range is just as likely as the low end.

In general, the changes in the year 2030 are modest, but by 2070 the high end of the range has very large, even startling changes. For example, the possible high end 2070 temperature increase of 2.7°C would be sufficient to make the average yearly temperature in Invercargill in 2070 equal to that of Wellington under the current climate.

The scenarios have been used as a guide to judge the likely extent and magnitude of impacts on the construction sector. Some aspects of climate change cannot yet be estimated, and therefore it has not been possible to quantify their impact on buildings.

Climate change can affect buildings directly (through weather and climate), but can also generate indirect impacts such as utility and material costs, and legislation. These impacts on houses are discussed later in this report, after the climate change scenarios are briefly described.

2.1 Temperature Changes

The most obvious effect of climate change is rising average temperatures. Current models and scenarios predict worldwide increases of 1-3.5°C by the year 2100 (Houghton et al, 1996). The actual changes in temperature in New Zealand will be slightly less than this, will vary for different regions, and probably have some seasonal pattern (Salinger 1990). The latest scenarios for temperature increases in New Zealand are given in Table 1. For changes in monthly temperature see Table 42 through Table 45 (pages 99-102).

Increases in average temperature may:

1. Reduce space heating and water heating requirements

2. Increase the incidence of overheating

3. Increase the load on air conditioning, and

4. Reduce the lifetime of building materials, especially plastics, coatings.

Table 1. Average temperature change for New Zealand.

Year	Temperature change
2030	+0.3 to +0.9°C
2070	+0.6 to +2.7°C

2.2 Rainfall

Changes in rainfall with climate change will have a very strong geographical pattern, and are highly sensitive to the scenario. Maps of the 2070 scenarios appear in Figure 1 and Figure 2. For the 2030 low scenario, the changes are decreases of up to 5% over most of New Zealand, except in South Canterbury and the Central North Island which have increases of up to 2%. For the 2030 high scenario all areas have an increase of up to 10%, except the Wellington and North Canterbury regions, which have no change or a <1% decrease. In 2070 the changes range from decreases from 0 to 15% for the low range scenario, to increases from 0 to 30% for the high range scenario.

The general pattern to the rainfall changes is that the Wellington and Canterbury regions have smaller changes than the rest of the country.

Contour maps of the rainfall changes for all scenarios are given in Figure 9 through Figure 14 (pages 108-109). Monthly precipitation changes are given in Table 46 through Table 49 (pages 103-106).

Changes in the annual amount of rainfall and increases in the average intensity of storms are expected to increase both the occurrence and intensity of heavy-rainfall events over New Zealand. The Annual Exceedence Probability (AEP) is the probability that in any one year a rainfall event of a specified duration exceeds a specified intensity. These AEPs may change by:

- **2030** No change through to a doubling of the AEP of heavy rainfall events.

- **2070** No change through to a fourfold increase in the AEP of heavy rainfall events.

Heavy rainfall may become both more common and more intense with climate change. This may lead to increases in the incidence and severity of flooding. Consequently, buildings may be flooded more often, and with greater damage per flood.

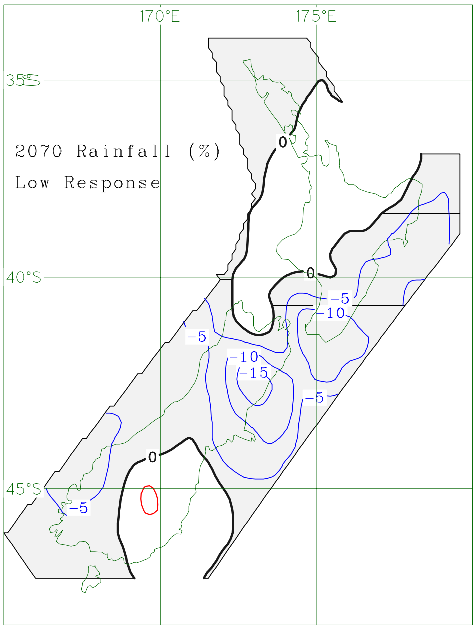

Figure 1. Percentage change in annual rainfall. 2070 Low end of range.

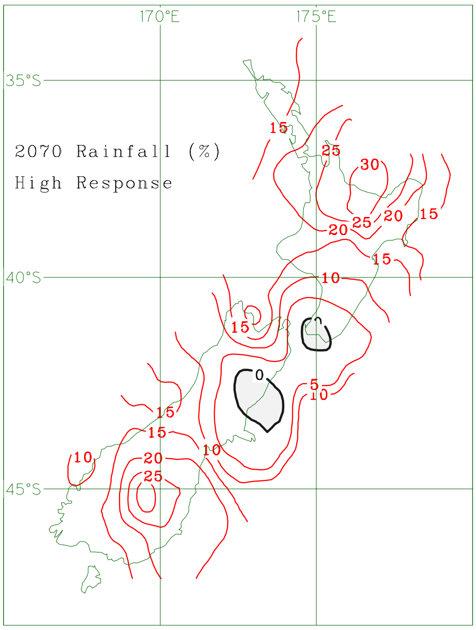

Figure 2. Percentage change in annual rainfall. 2070 High end of range.

2.3 Sea Level Rise

Current models indicate a probable rise of between 15 and 95 cm in mean sea level by the year 2100 and that "regional sea level changes may differ from the global mean value owing to land movement and ocean current changes" (Watson, Zinyowera, and Moss, 1996). Sea level rise appears to be the most certain effect of climate change, with rises of 10-25 cm recorded over the last 100 years (Houghton et al, 1996). Projected sea level rises for New Zealand are given in Table 2.

Sea level rise may affect housing directly through:

1. Increased coastal flooding
2. Increased foreshore erosion, and
3. Rising water table.

Table 2. Projected sea level rise.

Year	Sea level rise
2030	4-24 cm
2070	10-60 cm

2.4 UV Changes

In the short term, UV intensity is expected to increase until about 2015, and then decrease. UV intensity may *decrease* from current levels by about 6-7% by 2030, and be about 10% lower than current levels in 2070 (i.e., back to levels observed around 1975) provided that international agreements limiting ozone depleting chemicals (such as CFCs and Halons) are effective.

UV radiation is a major cause of polymer degradation (i.e. plastic, rubber, wood lignin), so changes in UV radiation are expected to change the rate of degradation, affecting the life span of many products used in buildings.

2.5 Net Solar Radiation

There is little reliable information available about possible changes to cloudiness or sunshine hours, so this impact has not been quantified. Changes in net solar radiation or total sunshine hours could result from changes in cloud cover (Salinger and Hicks, 1990), resulting in changes in the amount of overheating or underheating in houses. See section 18.10, page 95 for more information.

2.6 Wind Speed and Direction

There is no reliable information available from the NIWA climate change scenarios on changes in extreme wind or wind directions. This is unlikely to be resolved in the short term. Therefore the impact of changes in wind with climate change cannot be quantified at this stage. The likely effect of possible changes, should they occur, has been examined.

2.7 El Nino-Southern Oscillation (ENSO)

The New Zealand climate is closely linked to what happens with the ENSO cycle. It affects temperatures and rainfall, and also the formation of tropical cyclones. At present there is not much confidence in climate change model projections of the ENSO extremes with climate change, and the consensus view is the fairly noncommittal one that the ENSO extremes will continue to occur and changes in frequency and intensity are possible (Whetton *et al*., 1996). The impact of changes in ENSO have therefore not been quantified, though they are potentially an important part of the impact of climate change for New Zealand.

2.8 Tropical Cyclones

The research reviewed indicated that there would be little, if any, change to the incidence of tropical cyclones with climate change, and that the potential intensity of tropical cyclones is also likely to either remain the same or undergo a modest increase of up to 10-20%. However this result is uncertain, and a major change from previous analyses that indicated large increases in both the incidence and strength of tropical cyclones around New Zealand.

Increases in the incidence and severity of tropical cyclones in New Zealand could cause large scale damage to houses from high winds, heavy rain, flooding, landslips and coastal flooding.

3. LIKELY IMPACTS OF CLIMATE CHANGE FACTORS ON HOUSES

3.1 Decreased Winter Space Heating

Climate change factor	Temperature increase
Interactions	GHG emissions, summer overheating
Detailed Analysis	Section 7, page 42

Summary

By 2030 the required heating energy decreases by: Auckland 12-70%; Wellington 25-33%; Christchurch 4-14%; Invercargill 12-19%.

By 2070 the required heating energy decreases by: Auckland 69-79%; Wellington 29-86%, Christchurch 9-62%; Invercargill 15-51%.

There will be greater opportunity to heat houses entirely from passive solar heating by 2070, especially in the Auckland and Northland regions.

Recommendations

1. Increase public and industry awareness of good thermal design (especially passive solar) to maximise the benefits.

2. Increase public and industry awareness of GHG emissions of space heating to maximise emissions reductions.

Discussion

Less space heating will be required if temperatures increase with climate change. To quantify the reductions in heating energy, heating simulations of houses were performed using the ALF method (Bassett, Bishop, and van der Werff, 1990). The anticipated percentage reductions in space heating for several locations in New Zealand are given in Table 3. The range for each location and year reflects the possible range of temperature changes. The *percentage* reductions in heating energy were found to be almost the same for a house regardless of insulation level, orientation, thermal mass level, heating schedule, or thermostat temperature.

Table 3. Reductions in space heating energy with climate change.

	2030	**2070**
Auckland	12-70%	69-79%
Wellington	25-33%	29-86%
Christchurch	4-14%	9-62%
Invercargill	12-19%	15-51%

3.2 Decreased Water Heating Energy

Climate change factor	Increased temperatures
Interactions	None
Detailed Analysis	Section 8, page 50

Summary

By 2030 the required water heating energy decreases by 0.8-2.8%.

By 2070 the required water heating energy decreases by 1.8-8%.

Recommendations

None.

Discussion

Reductions in the required hot water heating energy of about 3% per 1°C increase in temperature are expected as a result of the warmer temperature of the cold water supply. If temperatures increase with climate change by the amounts expected in the NIWA scenarios then the required water heating energy will decrease by 0.8-2.8% by 2030, and by 1.8-8% by 2070.

3.3 Increased Overheating and Air-Conditioning Load

Climate change factor	Temperature increases
Interactions	Solar radiation changes
Detailed Analysis	Section 9, page 51

Summary

The number of days per year with uncomfortable indoor temperatures is expected to increase, markedly in some areas (see Table 4). Many areas may have a long summer ‘cooling season’ with climate change. Demand for house air-conditioning may increase.

Recommendations

Increase use of passive solar design principles to reduce overheating.

Discussion

To quantify the increase in overheating with climate change, the threshold for uncomfortable indoor temperatures was defined as an outdoor daily maximum temperature of 25°C or above. The number of days with temperatures exceeding this 25°C threshold is expected to increase with climate change (see Table 4). The future increases in Auckland and Christchurch would be enough to create a long summer ‘cooling season’ lasting a month or more.

This level of prolonged discomfort is unlikely to be tolerated by most house-owners, who would be forced to take mitigation measures, possibly by installing air-conditioning (and increasing the GHG emissions from energy use).

Not all houses will be equally affected by overheating. Those houses with good solar design features such as properly shaded north- and west-facing windows, minimal west-facing windows, or provision for effective ventilation should be least affected. Houses without such features, or poor solar design, could suffer severe overheating.

The change in air-conditioning load has not been quantified, as only a few percent of houses nationwide use air-conditioners (Roussouw, 1997).

Table 4. Number of days per year with uncomfortable outdoor temperatures (>25°C).

	Now	2030	2070
Auckland	20	25-37	31-81
Wellington	3	4-7	5-21
Christchurch	26	29-36	32-64
Invercargill	2	2-3	3-11

3.4 Greenhouse Gas (GHG) Emissions of Houses

Climate change factor	GHG emissions, carbon charges
Interactions	Temperature increase
Detailed Analysis	Section 10, page 53

Summary

GHG emissions from houses are mainly from CO_2 and, for most houses, occur mainly during occupancy. Houses could be modified to reduce their GHG emissions. Aspects for improvement include energy efficiency; fuel type; passive solar design; materials choice; size of house and amount of construction material; durability; and transportation demand. These options are most feasible for new homes, but retro-fitting is effective for some of these aspects.

Recommendation(s)

Increase understanding of the full life-cycle environmental impact of houses, including occupant effects, so that sensible and cost-effective strategies can be adopted if required.

Discussion

GHGs are emitted from houses at all stages of their life, from building material production, through construction, operation and demolition. CO_2 is by far the predominant GHG for houses at all stages of the life cycle, both in terms of quantity and the contribution to climate change.

Manufacturing GHG emissions for a 100 m^2 house range from approximately 6 tonnes to about 35 tonnes CO_2 equivalent, depending on house construction materials (Buchanan and Honey, 1994). Manufacturing emissions are currently much smaller than occupancy emissions for energy use for most houses (Jaques et al, 1997). Manufacturing GHG emissions are minimised by using locally sourced material, favouring timber over more GHG intensive materials like cement, steel, and aluminium. Maintenance GHG emissions may be minimised by using durable, low maintenance materials. A sensible compromise of production GHG emissions, durability and recyclability will give the lowest life-cycle GHG emissions.

Energy use during occupancy varies widely with the house type and location. Approximate annual CO_2 emissions for space heating are given in the following table. These figures are based on emission factors for thermal electricity. If gas is used directly for heating the emissions are approximately halved. These emissions will reduce if temperatures increase, by the same percentages as the space heating energy described in section 3.1, page 16.

Emissions for hot water heating are approximately 2000 kg per four-person household per year, assuming GHG emission factors for thermal electricity.

The thermal design of a house has a significant effect on the energy used for space heating. Improvements in the basic design of houses could reduce the life-time GHG emissions from energy use substantially. Examples include passive solar design, increased insulation, double glazing, and heat recovery.

Houses sited to maximise the opportunity for using public or pooled transport, or to minimise commuting distance would assist in minimising the GHG emissions for personal transport, which can easily exceed the occupancy GHG emissions of an entire household.

When houses are maintained or refurbished there is an opportunity for the owner to upgrade the energy and GHG performance of the house by installing energy efficient heating appliances (including solar), extra insulation, or reduce the environmental impact of the house by choosing appropriate materials and house designs. In the future, there is the possibility that some of these options could become mandatory for new and/or existing homes, though there are many cost and non-technical barriers.

Increased use of air-conditioning (currently very uncommon in houses) could result from increased incidence of overheating, which would increase both energy GHG emissions and direct emissions of refrigerants.

Table 5. Simulated annual GHG emissions for space heating of a 100 m^2 house for 1990, based on emissions for thermal electricity.

Location	**GHG emissions (kg CO_2 eq)**
Auckland	1414
Wellington	2911
Christchurch	3542
Invercargill	5891

3.5 Increased Costs due to Carbon or GHG Charges

Climate change factor	GHG emissions
Interactions	Temperature increase
Detailed Analysis	Section 11, page 67

Summary

Any form of carbon charge is expected to result in increased costs of building materials. The percentage increase in cost will probably be least for timber products, more for cement, much more for steel, and more still for aluminium. Costs for fuel and energy are also expected to increase if carbon charges are imposed. The increases in costs are not expected to be enough to strongly influence the choice of building materials or energy sources towards those with lower GHG emissions, except at the margins.

Recommendations

Adopt cost-effective energy efficiency measures to offset increased costs.

Discussion

Possible carbon charges, and energy efficiency and waste reduction legislation would impose compliance costs on the building industry. Costs could include measurement, auditing, legal and actual direct resource charges or taxes. The level of costs is uncertain at the moment, as is the time-table for implementation.

Carbon charges would increase energy costs for raw materials and manufacturing processes, and impose additional costs on steel, aluminium, and cement manufacturing. Timber would probably have the lowest price increase, more for cement, much more for steel and even for more for aluminium. As a rough estimate, assuming a carbon ‘charge’ of $100-$200 per tonne of carbon, the cost of a new 100 m^2 house would increase by $400-$2000, depending on the construction type. The future cost of carbon emissions is unknown, and could be substantially lower. See Section 11, page 67 for more details.

Changes in the availability and cost of resources may affect the construction industry by restricting or eliminating some building materials. Any reduction in the international competitiveness of New Zealand building-related industries could see them close or shift off-shore. The New Zealand construction industry is vulnerable to changes in supply as a consequence.

Fossil fuel prices are expected to rise with any form of carbon charge, though given the large component of fuel taxes in the overall price for fuel in New Zealand the percentage increase should be small. Carbon charges would increase costs for the transportation and construction sectors (Steiner 1990). Carbon charges of $100-$200 per tonne of carbon would increase the cost of average electricity by about 2.5% (with larger increases on peak electricity), and gas by about 5%.

3.6 Changes in Electricity Costs

Climate change factor	Temperature increase, GHG emissions, Rainfall
Detailed Analysis	None

Summary

Electricity prices could increase with increasing temperatures and carbon charges.

Recommendations

None

Discussion

Electricity prices could increase as the efficiency of thermal power stations and the electricity network would be reduced by increases in temperature (Mundy 1990). Expected decreases in heating energy demand as a result of temperature increases would reduce reliance on thermal stations, possibly reducing energy costs overall (Mundy 1990). GHG charges would directly increase electricity costs. Changes in rainfall patterns could lead to changes in the cost of hydro-electricity. Increased rainfall could give greater storage and lower costs, but the associated greater variability could lead to more frequent shortages, and more conservative (and hence costly) dam management practices (Watson, Zinyowera, and Moss, 1996).

3.7 Increased Inland Flooding

Climate change factor	Change in rainfall
Interactions	Sea level rise
Detailed Analysis	Section 12, page 70

Summary

More frequent and severe flooding is expected in all areas. The actual building damage of each flood event is also expected to increase. It may take decades after a change has occurred before the change can be detected, and perhaps even longer to firmly attribute climate change as the cause.

By 2030, no change through to a doubling of the probability (AEP) of flooding.

By 2070, no change through to a fourfold increase in the probability (AEP) of flooding.

Recommendations

1. Include the risks of increased flooding with climate change in flood management plans.

2. Precautionary approach to new development, and upgrading of flood protection.

3. Further research into the link between increased rainfall and increased flooding.

Discussion

The changes in heavy rainfall with climate change may result in more flooding, with consequent water damage to houses, drain damage, erosion and slips, and damage to services such as roads, pipes, and cables.

With climate change the historical flooding Annual Exceedence Probabilities (AEPs) may rise, increasing the frequency of flooding, and increasing both the incidence and extent of flood damage to houses. The actual cost of building damage is expected to equal or exceed the change in flooding AEP: a fourfold increase in the AEP could result in up to a tenfold increase in the cost of building damage (Smith et al). Existing flood protection works will not reduce this impact, and could even make it worse.

Even if the high end of these increases in flooding AEPs occur, it may take decades to determine if the AEPs have in fact changed, by which time it will be too late for changes in planning or NZBC requirements to reduce the impacts of climate change induced flooding on affected houses (see section 6, page 34).

Increases in the incidence and severity of flooding are likely to lead to increased flood insurance premiums, or withdrawal of insurance cover.

3.8 Increased Coastal Flooding, Erosion, and Rising Water Tables

Climate change factor	Sea level rise
Interactions	Rainfall, tropical cyclones, inland flooding
Detailed Analysis	Section 13, page 75

Summary

If sea levels rise, coastal flooding may become more frequent and severe. The increase in flooding risk is expected to be greatest for houses on sheltered coasts built near the high tide mark. Sandy foreshores may retreat, in the worst case by up to 50 m by 2070. Rising water tables may reduce the capacity of drainage systems, in the worst case causing flooding inland when stormwater systems and rivers cannot drain into the sea.

Recommendations

1. Adopt a precautionary approach to coastal development.

2. Revision of coastal flood hazard lines to account for possible sea level rise.

3. Allow for possible sea level rise in new drainage systems, coastal infrastructure, and buffer zones.

Discussion

Quantifying the change in flooding risk can only be done on a location by location basis as coastal flooding is caused by the combined effect of sea level, tides, storm surge and waves. Such studies are beyond the scope of this report.

The increase in flooding risk with sea level rise for a sheltered coast may be greater than for an exposed, stormy coast. Houses on a sheltered coast can be built closer to the sea level than on an exposed coast, as they do not have to have a large ‘safety margin’ for storm surge and waves. As the likely sea level rise is a large fraction of the ‘safety margin’ for these houses, the risk of flooding could increase dramatically. For many exposed coasts, the rise in sea level is much smaller than the storm waves, and so there would be less effect of changes in sea level.

A sea level rise of 15-95 cm could cause foreshores to retreat by 20-80 m in low lying sandy areas (Hicks 1990).

The water table is expected to rise in response to rising sea levels. In areas with an existing high water table, surface flooding may become more frequent, leading to damage to foundations and walls. Unbalanced or changing ground-water pressure could damage foundations. Sewerage and stormwater systems may also be damaged or rendered inoperable by rising sea levels (Mosley, 1990), possibly causing flooding well inland in low-lying areas.

Sea level rise is potentially a big impact of climate change for vulnerable, low-lying areas of New Zealand.

3.9 Degradation of Polymers

Climate change factor	Increased temperatures, UV changes
Interactions	Changes in wind speed and rainfall
Detailed Analysis	Section 14, page 77

Summary

The degradation rates of polymers (including plastic, rubber, PVC, sealants, wood and paint) may increase with increasing temperatures as follows:

By 2030 2-7% increase in temperature induced polymer degradation rates.

By 2070 4-20% increase in temperature induced polymer degradation rates.

These increased degradation rates may be offset in part by long-term decreases in UV radiation. PVC may suffer rapid degradation if the PVC surface gets much over 50°C, and this may happen more often with increased temperatures.

Recommendations

Further research into polymer degradation processes.

Discussion

The rate of degradation of many materials increases with increasing temperatures. Susceptible materials include plastics, rubbers, paint, varnish, fabric and wood. It is not possible to individually calculate the increase in degradation rates for all these materials as there are too many of them, the degradation processes are not necessarily well understood, and can be affected by other factors such as moisture and UV light (Andrady et al, 1995). However, a rough estimate of the generic change in degradation rates is given in Table 6, assuming that only temperature changes. (See Section 14, page 77 for details of the calculation). Long-term decreases in UV may offset some of this increase.

Some materials (e.g. PVC) may suffer much increased deterioration with increasing extreme temperatures.

Table 6. Increase in degradation rates with increasing temperatures.

Year	Temperature change	Estimated Degradation Rate Increase
2030	0.3-0.9°C	2-7%
2070	0.6-2.7°C	4-20%

3.10 Changes in Wind

Climate change factor	Wind speed and direction, tropical cyclones
Interactions	None
Detailed Analysis	Section 14, page 80

Summary

Current climate change science can make no reliable predictions about possible changes in wind. Even if structurally damaging winds do increase, it will take decades to confirm that increases have occurred, because these winds are extremely rare.

Recommendations

1. Further research into climate change effects on wind.

2. No current need to change design wind speeds for houses.

Discussion

Extreme wind causes damage to houses, especially to roofs and windows, and damage to services such as power and telephone lines. New Zealand timber framed houses already have their structural design dictated by wind zones (NZS 3604:1999). The risk is that with climate change the wind zones and wind exposure could change, perhaps exposing houses to winds they were not designed for.

A change in prevailing wind can affect ventilation, comfort, and building performance, especially for passively ventilated buildings. Increased corrosion may be a particular problem in coastal areas. If changes in prevailing winds change the exposure of a site, the structural design may be inadequate for the new conditions (NZS 4203, 1992).

The likely impacts of increases in the occurrence of structurally damaging wind have been analysed in this report (see section 14, page 80). The simplified method for determining design wind loadings in NZS 3604:1999 is somewhat conservative, so small increases in the occurrence of structurally damaging winds would probably not increase the risk of damage beyond that prescribed in the NZBC.

In any case, as structurally damaging winds are very rare, it may take decades to determine if the incidence of extreme winds has in fact increased at a given location (see section 6, page 34).

3.11 Increased Tropical Cyclones

Climate change factor	Tropical cyclones
Interactions	Sea level rise
Detailed Analysis	Section 16, page 82

Summary

Climate change science currently has several conflicting assessments of changes in tropical cyclones, ranging from no change to slight increases. The potential for damage to houses from any increase in tropical cyclones is so large that, despite the uncertainties, this potential impact must be taken very seriously.

Recommendations

Urgent further research into changes in tropical cyclones with climate change.

Discussion

When cyclones strike New Zealand they do substantial damage. Information from the Insurance Council of New Zealand shows that claims from cyclones over the last 10 years amounted to about $55 million dollars, with more than $50 million in 1988 from Cyclone Bola alone (Insurance Council, 1997). Any increase in cyclones in New Zealand would dramatically increase weather-related damage, including structural damage from wind, increased flooding, and increased landslips.

Caution dictates that the current conservative result be treated as provisional, until further research is done.

3.12 Increased Insurance Costs

Climate change factors	Change in rainfall, sea level rise, tropical cyclones
Interactions	None
Detailed Analysis	None

Summary

If increased rainfall or sea level rise leads to increases in flooding or storm damage, insurance premiums are expected to rise. In the worst case, insurance cover could be denied, marginalising affected communities.

Recommendations

None

Discussion

The insurance industry overseas is acutely aware of the risks imposed by climate change. National Pacific Insurance pulled out of Western Samoa because of the difficulty of buying re-insurance on the world market (Pacific Islands Monthly, 1992). At least 24 re-insurers pulled out of the Caribbean following major hurricane losses, making insurance more difficult to find and more expensive (Lloyds List, 1993). This could have serious implications for buildings in vulnerable areas, as insurance is mandatory for most housing loans; without it banks will not issue a loan or may foreclose. Insurers are likely to take a precautionary approach to climate change, leading to rising insurance costs and limitations or denial of cover in at-risk areas.

Likely increases in the incidence of flooding of one to four times by 2070 may increase the actual average annual damage to buildings in an urban area by much more, perhaps as much as 10 times in extreme cases (Smith et al). If tropical cyclones increase, there could be even larger increases in weather-related damage (Stark, 1987). Faced with this situation, insurers are sure to raise premiums by a similar amount, and may even decline cover, forcing the direct costs of flooding back onto house-owners, the community, or local and national government.

3.13 Changes in Timber Properties

Climate change factor	Temperature increase, increase in CO_2 levels, changes in rainfall
Detailed Analysis	None

Summary

Timber growth may be affected by temperature increases, CO_2 levels, and rainfall, possibly affecting the physical properties of wood and the relative costs of timber versus composite wood products.

Recommendations

None

Discussion

Increases in temperature and CO_2 may increase the growth rate of trees, encouraging earlier harvesting, with consequent lower stability and wood strength (Aldwell 1990). This could lead to a move from structural wood products to composite wood products, affecting price, availability and quality. The wood density is expected to increase with increasing growing temperatures, but this may not be enough to offset the more rapid growth. Some problems have been noticed recently with timber framing from young trees (O'Malley, 1998). It is difficult to assess if climate change would exacerbate this problem.

4. PRIORITISING IMPACTS

A myriad of possible impacts have been described. Some are more likely to occur than others, and some have more potential for damage than others. An attempt is made here to assign a priority to each impact for both further research, and for action. Ratings are given of the likelihood of an impact occurring with climate change, the severity of the impact (economic, social, and environmental costs), and the scale. Higher priorities are then assigned to larger scale, more severe impacts. These ratings are obviously somewhat subjective, but are designed to clarify a complex assessment.

Table 7. Risk-severity-priority matrix for impacts.

Impact	Likelihood	Severity	Scale	Research Priority	Action Priority
Winter heating energy	High	Low	National	C	B
Summer overheating	High	Med	Regional	C	B
Increased coastal flooding	High	High	Local	B	A
Increased inland flooding	Med	High	Local/ Regional	B	A
Change in wind	Low	Med	Regional	D	D
Change in tropical cyclones	Unknown	Ext. High	Regional	A	C
Increased polymer degradation	Low	Low	National	D	D
Carbon charges	High	Low	National	B	C
Changes in electricity costs	Med	Low	National	C	C
Increased insurance costs	Med	Low	Local	C	B
Changes in timber properties	Med	Med	National	C	C
GHG emissions of houses	High	Med	National	B	B

The highest research priority is for tropical cyclones, followed by flooding. The highest action priorities are for flooding.

Heating energy, overheating, carbon charges and GHG emissions have been assigned mainly B-C priorities, as the impacts are not as severe as flooding, and failure to take immediate action has less serious long-term consequences.

The Action Priority begs the question of who should be taking action, and who should bear the cost. For most impacts, action is required at many levels, from central, regional and local government, to the building industry and the public. This moves well outside the scope of this report, as achieving change in housing is a complex process. A companion report on Objective Two of this research programme examines perceptions and possible responses to climate change of house-owners and designers, and other stakeholders in the building industry (Saville-Smith, 1998).

5. CONCLUSIONS

All aspects of climate change are likely to affect houses. In this report a variety of levels of analysis have been used for the different effects, depending on how feasible it was to ‘model’ the particular impact on buildings, and also on the ‘certainty’ of the climate change scenario. As a result, some impacts have been well quantified, while others have not been quantified at all. These impacts are weighted and amalgamated into a ‘Sustainability Index’ in Objective Three of this programme (Camilleri, 2000b).

Climate change factors affecting houses have been identified. These are varied and numerous:

1. Extreme wind
2. Extreme temperatures
3. Tropical cyclones
4. Flooding
5. Sea level rise
6. Temperature increases
7. Extreme rainfall
8. UV radiation changes
9. Net solar radiation
10. Wind direction changes
11. Interaction of two or more climate change factors

Indirect factors affecting the construction industry are:

1. Changes in energy costs
2. Possible environmental legislation
3. Carbon and GHG charges
4. Insurance costs and availability

The effect of housing on climate change is mainly from GHG emissions during occupancy, with CO_2 by far the largest single GHG.

There is a large uncertainty in the climate change scenarios, which leads to a large uncertainty in the scale of impacts on houses. However, impacts may be significant by the year 2030 for all scenarios, and may become very large if the high end of the scenario range eventuates by 2070.

The required household space heating energy will decrease if temperatures increase. Reductions have been calculated for four locations, and the total energy demand for all New Zealand houses may decrease by 20% by 2030, and by up to 50% by 2070. Hot water energy demand is expected to decrease by about 3% per 1°C average temperature rise. Nationwide reductions of 2-8% are possible by 2070.

Greenhouse gas emissions per household may fall by a similar percentage as the heating energy, if occupant energy ‘service’ demand and house occupancy remains static. Even larger reductions could result if gas heating replaces electric heating.

The incidence of summer overheating will increase, most dramatically for the Auckland and Canterbury regions. The number of days with maximum temperatures over 25°C could rise from 20 to 25-37 by 2030, and to 31-81 by 2070 for Auckland, and similar increases for Canterbury. Faced with a 1-3 month ‘cooling’ season many house-owners, with poorly designed houses, may be forced to take steps to reduce overheating, perhaps by air-conditioning.

Changes in rainfall may decrease the return period of inland flooding by 1-4 times by 2070. This could cause significant impacts in vulnerable areas (primarily those already at risk from flooding), though it may take 10-50+ years before it can be concluded that the risk has increased significantly after a change in the pattern of flooding actually occurs. Increases in the annual cost of property damage in specific areas could be as much as 10 times the current costs.

It has been shown that there are limits to the ‘detectability’ of changes in intensity or return period of rare events such as flooding and structurally damaging winds, because both the current and future climate are not accurately defined. Long periods may be needed to ‘prove’ that a change in a climate risk factor has in fact occurred, and even then it may be difficult to attribute climate change as the cause. Therefore there may not be a clear-cut case for taking action until it is too late.

Rising sea levels would increase the flooding risk in vulnerable, low-lying areas, and potentially expose some homes not considered at risk previously. Large decreases in the return period of coastal flooding are anticipated in areas where the sea level rise is a large fraction of the total present flood height. Some Territorial Authorities are already revising coastal hazard lines. Stormwater and sewerage systems, coastlines, coastal bores, and low-lying roads are also at risk.

There is no consensus about changes in wind, but even if there were, the basic New Zealand Building Code (NZBC) design wind speeds are probably conservative enough that any likely change in risk would be difficult to detect.

There is no consensus about changes in tropical cyclones, but huge impacts are expected if the north of New Zealand becomes a cyclone zone. Hurricane force winds would be expected to structurally damage most homes, and heavy rain and high seas would cause major coastal and inland flooding.

Changes in the El Nino and La Nina weather pattern are also uncertain, and would have significant associated impacts which have not been quantified.

Rates of polymer degradation (plastics, paints, rubber, wood) may increase due to increasing temperatures, but these increases may be offset by reductions in UV in the long term.

House-owners may face increased insurance costs, energy costs and material costs. If carbon charges are introduced they would be expected to increase the cost of building materials, and perhaps change the availability of materials, but the level of costs is uncertain. Most or all of the cost to house-owners could be offset by careful design and suitable energy efficiency measures.

It is recommended that the top priority for climate research should be the possible changes in tropical cyclones and flooding. The top priorities for action are taking steps to mitigate the impacts of coastal and inland flooding.

APPENDICES: SECTIONS 6-18

6. DETECTION OF CHANGES IN THE INCIDENCE OF EXTREMES

1998 was a year of extremes for the New Zealand climate: prolonged droughts in Marlborough, Hawkes Bay, and Canterbury; record high summer temperatures in Auckland; major flooding occurred in the Waikato and Bay of Plenty with slips damaging many homes and temporarily cutting many state highways from north of Auckland to the Manawatu gorge. The first half of 1998 was the hottest six months ever recorded worldwide, and the year before that the hottest year (The Dominion, July 16, 1998). The media has faithfully reported all of these facts and has been tempted to single out climate change as a cause, but is such a conclusion justifiable?

Mosley (1990) pointed out that "the true impacts of climate change on flooding would likely not be perceptible, simply because of its episodic or localised nature". This statement needs closer examination, as the implications are central to risk management issues in the face of climate change.

The Annual Exceedence Probability (AEP) is the probability in any year that a threshold will be exceeded. For example, if the AEP flood level of 2 m is 3%, then there a 3% probability *each year* that a flood of 2 m *or greater* will occur.

A house located at the 2% AEP flood line is expected to be flooded once in a 50-year period (on average). If the AEP doubles or quadruples, then it is expected to be flooded two or four times respectively in a 50-year period. The annual average damage (AAD) has been shown to increase by more than these factors since flooding occurs more often, with increased flood height, increasing both the numbers of houses damaged, and the cost of damage to each house (Smith et al). The risk to an individual house has changed, as has the expected average cost of flooding damage, but the impact of the change will be felt only when flooding occurs. When this flooding occurs is random, and could happen at any time in the 50-year period.

At what time can it be said that the increased risk of flooding with climate change has had an impact on the house? Is it when the AEP changes, or when the house is flooded once too often? In both cases, the impact occurs after unacceptable (and perhaps avoidable) damage occurs.

To detect a change in the incidence of extreme events, a long period of 'new' observations must be obtained so it can be compared to the 'current' historical record. For example, if a sharp increase in flooding incidence occurred tomorrow, it could take many years of observations before the increase was detected, simply because severe flooding occurs infrequently, even for AEPs of 10%.

The purpose of this section is to examine what level of change in the incidence of extreme or rare events can be detected within a specified time. This is done by determining the detectability of changes in the incidence of extreme for:

1. Changes in the Frequency of Rare Events (AEP $\leq$ 10%)

2. Detecting Changes in Flood Flow (AEP = 1%)

3. Changes in Wind/Rain Intensity-Return Period Relationship

4. Changes in Mean Rain/Flood Volume

Each of these cases is discussed in the following sections.

6.1 Changes in the Frequency of Rare Events

This section addresses two questions:

1. How often does a rare event have to occur in a given time period, before it can be concluded that the AEP has changed?

2. How small a change in the AEP is detectable in a given time period?

These questions are important because the answers indicate whether or not changes in rare events due to climate change can actually be detected soon enough to take mitigation steps.

The Annual Exceedance Probability (AEP) is the probability that some threshold will be exceeded in a given year. The threshold might be a wind gust speed, a rainfall intensity, or a flooding height or flow. If the AEP is very low (≤10%) then the probability that this threshold is exceeded more than once in a given year is extremely low (<0.5%), and since the occurrences in all years are independent, the occurrence of extremes can be modelled by the binomial distribution with probability of success equal to the AEP. (The binomial distribution is used to describe the statistics of simple success/failure outcomes such as coin tosses, where the future outcome is unaffected by previous outcomes (Spiegel, 1992).)

A rare event with an AEP of 0.1% (a 1,000 year return period) is considered as an extreme example, to demonstrate how difficult it is to detect changes in the occurrence of rare events. This is modelled as a binomial distribution with probability of success equal to 0.1%. In 50 years the probabilities of exceeding the threshold a given number of times (given in brackets) are:

$$p(0) = 95\%$$

$$p(1) = 5\%$$

$$p(>1) = 0.1\%$$

So, given that in 50 years the threshold was exceeded 0, 1, or more than 1 times, what can be inferred about the AEP? How many times must the threshold be exceeded in 50 years to conclude that the AEP has increased? To determine if the AEP has increased, take the null hypothesis that the actual AEP is 0.1% and apply a one-sided binomial test at a 5% significance level. The results are given in the following table:

Table 8. Conclusions of a binomial test, at the 5% level of significance.

No. Occurrences in 50 years	Is AEP > 0.1%?
0	No
1	borderline
2	yes

If the threshold is not exceeded, the conclusion is that the AEP is not >0.1%. If the threshold is exceeded once, then the no conclusion can be made about changes in the AEP. Only if the threshold is exceeded twice or more can it be concluded that the new AEP is >0.1%.

The second question is: How small a change in the AEP is detectable in a given time period? To answer this question, look at the same problem in a different way: if the AEP has in fact increased, how easily can this be detected?

If the AEP increases four fold from 0.1% to 0.4% then for the new AEP, the probabilities of X occurrences in 50 years are:

$$p(0) = 82\%$$

$$p(1) = 16\%$$

$$p(>1) = 1.7\%$$

To conclude that the AEP has increased above 0.1%, there need to be two or more occurrences in 50 years. At the new AEP of 0.4%, there is only a 1.7% chance of this occurring, so it is very unlikely that the increase in AEP from 0.1% to 0.4% will be detected. To get a 50% chance of detecting an increase in 50 years, the AEP must be ≥5%, an increase of 50 times!

Thus the AEP would have to increase dramatically to be detectable over a 50-year period. Any likely increase in the AEP from 0.1% would simply not be detectable over the time-spans considered in this report, 35-75 years.

The same procedure can be used to calculate the increase in the AEP required before it could be detected at a 5% significance level for a range of initial AEPs. Results are in

Table 9, page 38. From these figures it is obvious that only large increases in AEP are detectable for most initial AEPs. Only for an initial AEP of 5% or more is the increase in AEP much less than four times, and then only over 25 to 50 year observation periods.

In terms of acceptable risks to houses as defined by the NZBC, only changes in the risk of minor structural damage (AEP 5-10%) are likely to be detectable within the life-time of a house (50 years). Changes in the risk of major structural damage (AEP ≤ 2%) are unlikely to be detected in a 50-year time period. For example, climate change related changes in flooding AEP are expected to range from no change to an increase of four times, and be undetectable over a 50-year time period if the initial AEP is <2% (see section 12, page 70).

Table 9. Change in return period required to conclude an increase at the 5% level of significance for various annual exceedance probabilities.

Annual Exceedance Probability (AEP)	No. of years observed	No. of occurrences required to detect increase	Required AEP to have a 50% chance of detecting increase	Increase in AEP to have a 50% chance of detecting increase
0.1%	50	≥2	5%	50.0x
1%	50	≥3	5%	5.0x
	25	≥2	7%	7.0x
	10	≥2	16%	16.0x
2%	50	≥4	9%	4.5x
	25	≥3	24%	12.0x
	10	≥2	26%	13.0x
5%	50	≥6	14%	2.8x
	25	≥4	19%	3.8x
	10	≥3	36%	7.2x
10%	50	≥10	19%	1.9x
	25	≥5	19%	1.9x
	10	≥4	36%	3.6x

6.2 Detecting Changes in Flood Flow

The following analysis is based on the method and results of flood frequency estimation by McKerchar and Pearson (1989).

The extreme values for floods can be modelled by using Extreme Value Theory, based on the statistics of Extreme Value (EV) distributions. For instance, for New Zealand the 1 in 100-year flood flow (1% AEP) is estimated from EV distributions fitted to historical data. By using the EV distribution, reasonable estimates of the 1 in 100-year flood flow can be made with as little as 25 years of records. The accuracy of these estimates depends primarily on the number of years observed, and to a lesser extent on the actual shape of the fitted EV distribution. Typical values of the percentage error versus the number of years are given in Table 10, page 39.

Table 10. Relationship between the number of years of observations and the accuracy of the estimate of 100-year flood flow.

No. of years	Theoretical maximum percentage error in 100-year flood flow rate
1	100%
5	44%
10	31%
20	22%
30	18%
50	14%
100	10%

Typical errors in actual estimates of the 100-year and 50-year flood flow for New Zealand rivers are 28% and 26% respectively (McKerchar and Pearson, 1989). These errors are quite large because the number of years of record is short (typically 10-20 years) for many New Zealand rivers.

To detect a change in the 100-year flood flow, a new period of observation must be used to estimate the new 100-year flood flow, and then compared to the old estimate to see if it is significantly different. To do this use the z-test to determine if an increase of a factor *k* in the 100-year flood flow (Q_0) can be detected in a given time period. The following quantities are defined:

Current 100-year flood flow: Q_0

New 100-year flood flow: $Q_1 = (1+k)\cdot Q_0$

Numbers of years of recording new flood flow: N_1

Standard deviation of Q_0: $\sigma_0 = 0.28\cdot Q_0$

Standard deviation of Q_1: $\sigma_1 = Q_1/\sqrt{\ } N_1$

Then the z test statistic is:

$$z = \frac{Q_0 - Q_1}{\sqrt{\sigma_0^2 + \sigma_1^2}}$$

$$= \frac{kQ_0}{\sqrt{(0.28\cdot Q_0)^2 + (1+k)^2 Q_0{}^2 / N_1}}$$

$$= \frac{k}{\sqrt{0.28^2 + (1+k)^2 / N_1}}$$

Take the null hypothesis that the flow rates are equal, $Q_1=Q_0$. The alternate hypothesis is that $Q_1>Q_0$, which is accepted on the basis of a one-sided test at the 5% significance level if $z > 1.645$. Some values of z for various combinations of percentage increase (k) and N_1 are:

Table 11. z statistic for various observation periods and increases in flood flow.

		% increase		
		10%	**50%**	**100%**
Number of years of new flood flow record, N_1	1	0.08	0.32	0.50
	10	0.22	0.9	1.445
	50	0.31	1.4	**2.5**

The only case in the table where there is a statistically significant increase at the 5% level is when the 100-year flood flow was for 100% increase in flow (k=1) and N_1=50 (shown in **bold** in the table), ie. a doubling of the flow observed over 50 years. The precise threshold for detectability of a doubling of the 100-year flood flow is 15 years.

A doubling of the 100-year flood flow is a massive increase, as for all major New Zealand rivers the 200-year return period flood flows are only between 7 and 10% above the 100-year return period flood flow (McKerchar and Pearson, 1989). So if k=0.07-0.14, this means it is practically impossible to detect a halving of the return period, no matter how long the observation period. Even the 400 year return period flood flows are only 16 to 28% above the 100-year flood flow (which itself has errors of about 28%), so even a reduction in the return period of four times is undetectable.

In conclusion, any likely change in the 1 in 100-year (1% AEP) flood flow induced by climate change would be undetectable within a 50-year time frame.

6.3 Changes in Wind/Rain Intensity-Return Period Relationship

There would be similar difficulties in detecting changes in the rainfall intensity-return period relationship as for the 100-year flood flow. Typical errors in the 10 minute, 10 year return period rainfall intensity are 10-20%, and a halving of the return period to five years only increases the 10 minute rainfall by about 5-20% (Coulter and Hessell, 1980). These figures are comparable to those for the 1 in 100- year flood flow so there would be similar detectability problems.

Typical errors in the 50-year return period wind speed are 5-15% (De Lisle, 1965). From the properties of the EV distribution, similar errors would be expected in the 20 year return period wind speed (for the serviceability wind limit). The ultimate limit for structural failure as defined by the Building Code is at about the 500-year return period wind speed, which would be expected to have much larger errors. Changes in the serviceability wind speed should be detectable over a long enough period, but changes in the ultimate limit would not be detectable. See section 15, page 80 for additional discussion on structural design for extreme winds.

6.4 Changes in Mean Rain/Flood Volume

Changes in mean annual rainfall would be much easier to detect than changes in rainfall intensity-return period relationships, as the standard error for mean annual rainfall is typically only a few percent (NZMS, 1973). Therefore detecting small changes, or changes in a short time period is much easier. However, changes in mean annual rainfall do not necessarily imply changes in the frequency of extreme events above a certain threshold.

Changes in mean annual flood would be more difficult to detect, because the measurement errors are fairly high, typically 5-20% (McKerchar and Pearson, 1989). The errors are high because the actual distribution of annual peak flood flows varies over a wide range and is skewed.

6.5 Other Methods

There are a number of other statistical techniques available for determining if the underlying probability distribution has changed during the observation of a time series of data. The author considers it unlikely that the application of these tests would significantly change the findings of this section. More research is needed to confirm this.

6.6 Summary

In summary, it takes many years of observation to determine if the frequency of a rare event has changed. The exposure to flooding or wind damage risk of a house is required to be quite low by the Building Code, typically a 0.1-2% annual risk for major damage, and a 5-10% annual risk for minor damage. These are rare events, statistically speaking, and the likely changes in the AEPs small enough that it may take at least 10 to more than 50 years, and possibly much longer, to find out if climate change has in fact changed the risks.

Detecting changes in rainfall, flooding, or wind speed – return period relationships is also difficult, as the sampling errors in the historical estimates are large, and if the errors are comparable to the expected percentage increases with climate change, detecting changes may well be impossible. Long observation periods will be needed to determine if significant changes have in fact occurred.

Even if changes are detected, it may be difficult to attribute them to the effects of climate change, as there is already much year-to-year and long-term variation in the climate.

In conclusion, when risk management decisions are made about rare events over the next 50 years, it is unlikely that they will have strong evidence that changes have in fact occurred, or that any observed changes are attributable to climate change, in flooding, extreme rainfall, or extreme wind.

7. BUILDING HEATING ENERGY

The results of climate change models suggest increases in average temperatures are likely. As average temperatures increase, the amount of energy required to heat a house should decrease. In this section, estimates of the reduction in heating energy for typical houses in a variety of locations are provided.

The ALF (Annual Loss Factor) (BRANZ, 1990) method can be used to estimate the yearly heating energy required to maintain a given heating schedule in a house. ALF is not an hour by hour simulation, but is based on the results of large numbers of detailed simulations. A new version of ALF is under preparation and was used for this analysis (Stoecklein and Bassett, 1999). ALF 3 was used together with the climate change scenario temperatures to calculate the changing heating energy requirements for a reference building at four sites. Sites chosen were Auckland, Wellington, Christchurch, and Invercargill[iii], and modified by the climate change temperature scenarios for 2030 and 2070.

A series of ALF 3 calculations were performed for a 100 m² reference house under several heating regimes (night only, morning and night, daytime, 24 hours) for the temperature scenarios for the years 2030, 2070 and a reference average year under current climatology. The reference house was single level and rectangular with dimensions 8 m x 12.5 m and a 2.4 m ceiling height. Simulated buildings were insulated at levels required by NZS 4218:1996, as well as at lower levels to reflect the current housing stock. The effect of building orientation was investigated.

The combination of all the variables with the six climate change scenarios at four sites gives a total of 1152 simulation runs. There are too many to present in total in any meaningful way, so results have been summarised.

Heating schedules:	17:00-23:00
(Hours of heating used)	7:00-9:00 & 17:00-23:00
	7:00-23:00
	24 hours
Set points:	16°C
(Internal temperatures)	18°C
	20°C

‘Insulated’ houses R-values according to NZS 4218:1996, Zone 1:

Ceiling:	R1.9
Walls:	R1.5
Floor:	R1.3

[iii] Auckland - Whenuapai Aero, Wellington - Kelburn, Christchurch Gardens, and Invercargill Aero meteorological stations.

‘Uninsulated’ houses (R-values based on figures from Isaacs and Trethowen (1985)):

Ceiling:	R0.7
Walls:	R0.8
Floor:	R0.8

Thermal Mass Level:

Low Mass: Suspended timber floor, timber frame.

High Mass: Concrete slab floor (150 mm thick, perimeter insulated), timber frame.

7.1 Effect of Heating Schedule and Set Point

The heating schedule and temperature set point affect the required heating energy (for an example, see Table 13, page 45). As expected, a higher set point results in a higher heating requirement, as does a longer heating schedule. Making some sense of this mass of information is difficult, so in Table 14, page 46 these figures are expressed as a percentage reduction of the heating requirement. The percentage reduction is very similar for all heating schedules and set points. Reductions are slightly higher for lower set points, and slightly higher for shorter heating schedules (Figure 3, page 48). The range of variation generally is not large, so it is reasonable to take an average over all heating schedules and set points as being representative of the energy reductions for a particular house type.

It should be noted that the absolute energy use varies widely from location to location (see Table 16, page 49).

7.2 Effect of House Type

Three other house construction types were also simulated: low mass uninsulated, high mass insulated, and high mass uninsulated. The percentage reductions in heating energy for these house types were also little affected by the heating schedule and set point. In addition, the average percentage reduction for all house types was similar for all scenarios (Table 15, page 47).

7.3 Effect of House Orientation

The same house layout was simulated using NE, NW, and S orientation. Again, the percentage reduction in heating energy was found to change little as the orientation changed. Houses in the most southerly latitudes were the most stable with respect to orientation, perhaps because solar gains are a smaller fraction of the total energy requirement than for houses in the more northerly latitudes.

7.4 Limitations of the ALF 3 Method

The ALF 3 method had to be adapted to work for some Auckland some climate change scenarios, as some Auckland temperatures under climate change were outside the design range of ALF 3. Adaptations were done with the assistance of the ALF 3 designer. The model assumes that heating will be used in a particular month if the average monthly temperature is less than 11.5°C. For the 2070 medium and high Auckland scenarios, and the Wellington 2070 high scenario this criteria was not met, so ALF 3 did not heat the homes. To adapt ALF 3 the simulations were forced to heat for the month of July, even if the average monthly temperature was above 11.5°C. In these cases the percentage of useful energy was calculated incorrectly, as the internal gains and solar gains were often larger than the required heating energy. This caused ALF 3 to produce negative heating energies, or in some cases heating energies larger than the base cases. In these cases the required heating was determined without considering internal or solar gains, and so will be an upper limit of the required heating energy.

The estimates for Auckland provide a valuable insight into the magnitude of the reductions in heating energy. High mass buildings should be able to utilise more of the solar gains (Pollard and Stoecklein, 1997), so the actual required heating energy for the high mass buildings in Auckland would be expected to be even lower than suggested here.

7.5 Conclusion

The percentage reduction in heating energy is fairly uniform for a location and climate change scenario, independent of the house construction type, insulation, thermal mass, heating schedule, setpoint and orientation. Estimated reductions for the climate change scenarios at four locations are given in Table 12.

Table 12. Average reduction in heating energy as a percentage of the base case, averaged across all house types.

	2030 Low	2030 High	2070 Low	2070 Med	2070 High
Auckland[iv]	12%	>70%	>69%	>73%	>79%
Wellington	25%	33%	29%	58%	86%
Christchurch	4%	14%	9%	39%	62%
Invercargill	12%	19%	15%	30%	51%

[iv] The ALF3 model had to be modified to generate the figures for Auckland for all but the 2030 low scenario. They are a lower limit of the actual reductions in heating energy, which could in fact be as high as 100%.

Table 13. Heating energy for low mass uninsulated north-facing house (kWh/yr).

Setpoint	16°C	16°C	16°C	16°C	18°C	18°C	18°C	18°C	20°C	20°C	20°C	20°C
Heating Schedule	17:00-23:00	7:00-9:00 & 17:00-23:0	7:00-23:00	24 hours	17:00-23:00	7:00-9:00 & 17:00-23:0	7:00-23:00	24 hours	17:00-23:00	7:00-9:00 & 17:00-23:0	7:00-23:00	24 hours
Auckland, 2070, Low	222	542	338	1023	209	1229	1397	2089	453	1488	2071	2842
Auckland, 2070, Med	120	381	100	676	188	1035	1105	2012	360	1420	2008	2542
Auckland, 2070, High	18	219	0	330	208	840	814	1599	280	1416	1855	2287
Auckland, 2030, Low	818	2047	2579	4312	1486	3018	3821	6344	2201	4084	5380	8586
Auckland, 2030, High	191	494	268	920	199	1171	1311	2057	425	1463	2046	2749
Auckland, Base	977	2207	2713	4665	1690	3266	4117	6827	2440	4387	5792	9174
Wellington, 2070, Low	1671	3502	4491	7522	2596	4880	6409	10352	3556	6317	8596	13375
Wellington, 2070, Med	814	2174	2895	4556	1467	3079	4043	6544	2177	4122	5551	8769
Wellington, 2070, High	139	411	144	741	253	1071	1160	2092	389	1693	2265	2854
Wellington, 2030, Low	1787	3688	4724	7917	2744	5116	6728	10846	3734	6600	8996	13966
Wellington, 2030, High	1542	3298	4236	7085	2431	4617	6056	9802	3357	6002	8152	12716
Wellington, Base	2501	4854	6235	10383	3648	6576	8731	13906	4822	8336	11473	17611
Christchurch, 2070, Low	2826	5526	7137	11862	4085	7420	9885	15746	5375	9357	12898	19827
Christchurch, 2070, Med	1777	3785	4883	8153	2748	5230	6893	11136	3758	6743	9188	14324
Christchurch, 2070, High	943	2463	3267	5196	1647	3449	4544	7354	2409	4571	6176	9750
Christchurch, 2030, Low	2985	5784	7478	12406	4285	7740	10329	16416	5615	9735	13442	20621
Christchurch, 2030, High	2646	5235	6756	11250	3859	7059	9387	14991	5105	8929	12284	18930
Christchurch, Base	3124	6010	7777	12880	4459	8018	10717	16998	5823	10065	13917	21312
Invercargill, 2070, Low	4620	8656	11481	18649	6364	11279	15383	24050	8139	13942	19578	29675
Invercargill, 2070, Med	3455	6707	11616	14514	4895	8868	15553	18965	6370	11081	19773	23634
Invercargill, 2070, High	2485	5055	6698	10972	3654	6796	9178	14574	4863	8605	11952	18391
Invercargill, 2030, Low	4833	9002	11948	19375	6629	11702	15980	24937	8455	14441	20303	30724
Invercargill, 2030, High	4406	8309	11014	17919	6097	10853	14785	23157	7821	13439	18849	28618
Invercargill, Base	5506	10197	13560	21936	7489	13181	18038	28091	9505	16204	22821	34482

Table 14. Percentage reduction in heating energy for low mass insulated north-facing house.

Setpoint	16°C	16°C	16°C	16°C	18°C	18°C	18°C	18°C	20°C	20°C	20°C	20°C	
Heating Schedule	17:00-23:00	7:00-9:00 & 17:00-23:0	7:00-23:00	24 hours	17:00-23:00	7:00-9:00 & 17:00-23:0	7:00-23:00	24 hours	17:00-23:00	7:00-9:00 & 17:00-23:0	7:00-23:00	24 hours	Average
Auckland, 2070, Low	65%	72%	88%	77%	87%	57%	64%	62%	90%	54%	52%	63%	69%
Auckland, 2070, Med	81%	81%	96%	85%	82%	64%	71%	68%	92%	57%	59%	65%	75%
Auckland, 2070, High	97%	89%	100%	93%	70%	71%	79%	75%	93%	63%	65%	65%	80%
Auckland, 2030, Low	27%	3%	-2%	6%	19%	8%	5%	7%	14%	8%	7%	7%	9%
Auckland, 2030, High	70%	75%	90%	79%	86%	59%	66%	64%	90%	53%	54%	64%	71%
Auckland, Base	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Wellington, 2070, Low	39%	27%	24%	27%	33%	27%	26%	26%	29%	25%	25%	24%	28%
Wellington, 2070, Med	76%	48%	41%	52%	67%	53%	50%	52%	60%	52%	50%	50%	54%
Wellington, 2070, High	93%	90%	98%	92%	88%	82%	86%	84%	95%	77%	79%	79%	87%
Wellington, 2030, Low	34%	24%	21%	23%	28%	23%	22%	22%	25%	22%	22%	21%	24%
Wellington, 2030, High	45%	31%	28%	31%	38%	31%	29%	30%	34%	29%	29%	28%	32%
Wellington, Base	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Christchurch, 2070, Low	12%	8%	8%	8%	10%	8%	8%	8%	9%	8%	7%	7%	8%
Christchurch, 2070, Med	50%	37%	33%	36%	43%	36%	35%	35%	39%	34%	34%	33%	37%
Christchurch, 2070, High	78%	53%	48%	57%	70%	57%	54%	56%	64%	56%	55%	54%	58%
Christchurch, 2030, Low	5%	4%	4%	4%	5%	4%	4%	4%	4%	3%	3%	3%	4%
Christchurch, 2030, High	19%	13%	12%	13%	16%	13%	12%	12%	14%	12%	12%	11%	13%
Christchurch, Base	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Invercargill, 2070, Low	17%	15%	15%	15%	16%	15%	15%	14%	15%	14%	14%	14%	15%
Invercargill, 2070, Med	41%	35%	14%	34%	37%	34%	13%	33%	35%	33%	13%	32%	29%
Invercargill, 2070, High	59%	50%	48%	49%	55%	49%	48%	48%	52%	48%	48%	47%	50%
Invercargill, 2030, Low	13%	12%	11%	12%	12%	11%	11%	11%	11%	11%	11%	11%	11%
Invercargill, 2030, High	22%	19%	18%	18%	20%	18%	18%	18%	19%	18%	17%	17%	18%
Invercargill, Base	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 15. Reduction in heating energy for different house types. Averaged across heating schedules and set points.

	Low mass, insulated	Low mass, uninsulated	High mass, insulated	High mass, uninsulated	Average
Auckland, 2070, Low	69%	74%	67%	67%	69%
Auckland, 2070, Med	75%	79%	69%	69%	73%
Auckland, 2070, High	80%	83%	76%	76%	79%
Auckland, 2030, Low	9%	8%	14%	14%	12%
Auckland, 2030, High	71%	75%	64%	69%	70%
Wellington, 2070, Low	28%	27%	31%	31%	29%
Wellington, 2070, Med	54%	55%	61%	61%	58%
Wellington, 2070, High	87%	88%	84%	84%	86%
Wellington, 2030, Low	24%	23%	27%	26%	25%
Wellington, 2030, High	32%	31%	35%	35%	33%
Christchurch, 2070, Low	8%	8%	9%	9%	9%
Christchurch, 2070, Med	37%	36%	41%	41%	39%
Christchurch, 2070, High	58%	59%	65%	65%	62%
Christchurch, 2030, Low	4%	4%	4%	4%	4%
Christchurch, 2030, High	13%	13%	15%	15%	14%
Invercargill, 2070, Low	15%	15%	15%	15%	15%
Invercargill, 2070, Med	29%	29%	31%	31%	30%
Invercargill, 2070, High	50%	49%	53%	53%	51%
Invercargill, 2030, Low	11%	11%	12%	12%	12%
Invercargill, 2030, High	18%	18%	19%	19%	19%

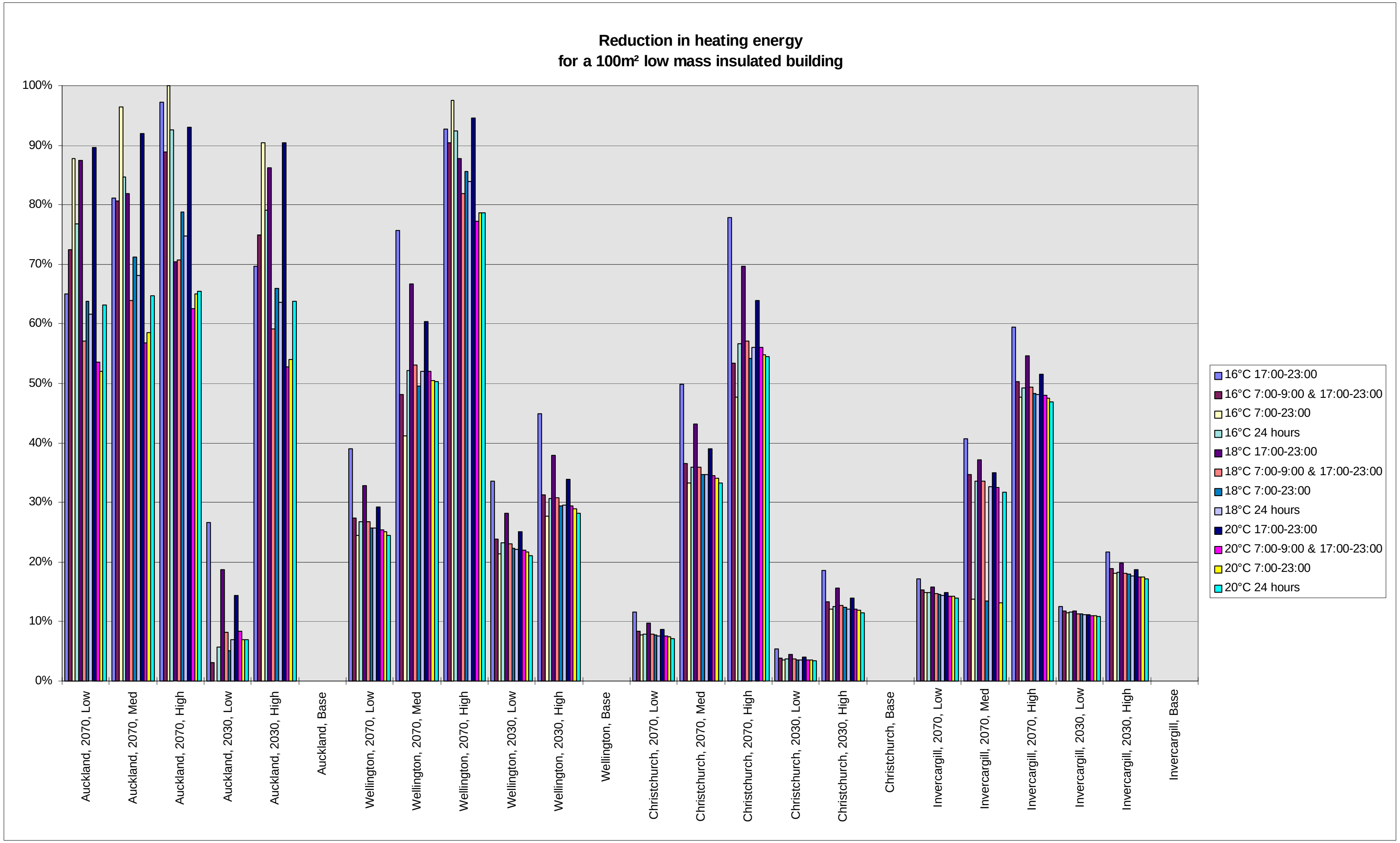

Figure 3. Reduction in heating energy for a 100 m² low thermal mass insulated house.

Table 16. Heating energy and CO_2 emissions under climate change scenarios for 100 m^2 low mass house insulated to NZS 4218:1996 with heating schedule 7-9am and 5-11 pm and 18°C set point.

Location	**Scenario**	**Energy Consumption (kWh/yr)**	**Percentage Reduction**	**CO_2 emissions (kg)[1]**
Auckland	Base	2210	0%	1414
	2030, Low	2030	8%	1299
	2030, High	902	59%	577
	2070, Low	946	57%	605
	2070, Med	797	64%	510
	2070, High	647	71%	414
Wellington	Base	4549	0%	2911
	2030, Low	3496	23%	2238
	2030, High	3144	31%	2012
	2070, Low	3329	27%	2130
	2070, Med	2136	53%	1367
	2070, High	824	82%	528
Christchurch	Base	5534	0%	3542
	2030, Low	5328	4%	3410
	2030, High	4830	13%	3091
	2070, Low	5094	8%	3260
	2070, Med	3543	36%	2268
	2070, High	2374	57%	1520
Invercargill	Base	9204	0%	5891
	2030, Low	8165	11%	5226
	2030, High	7535	18%	4823
	2070, Low	7851	15%	5024
	2070, Med	6111	34%	3911
	2070, High	4661	49%	2983

[1] Assuming 100% efficiency electric heater at marginal CO_2 emissions of 0.64 kg/kWh.

8. HOT WATER HEATING

Preliminary results from the HEEP study suggest that for each 1°C rise in average temperature the required hot water heating energy drops by approximately 3% (Stoecklein and Isaacs eds., 1998). Using the climate change scenarios, the average percentage reductions in hot water energy requirements are given in Table 17. These reductions are small, but significant on a national scale since hot water accounts for a substantial fraction of energy use in the home. There is likely to be some small additional variation from north to south.

These figures will be revised as more data is analysed from the HEEP study.

Table 17. Average percentage reduction in hot water energy requirements.

2030, Low	0.8%
2030, High	2.8%
2070, Low	1.8%
2070, High	8.0%

9. BUILDING OVERHEATING IN EXTREME TEMPERATURES

The heat-wave in Auckland during the summer of 1997-98 drew the attention of many building occupants to the poor performance of their buildings in high temperatures. The BRANZ Advisory Helpline "received many inquiries from people seeking relief from the unusually high temperatures and humidity" (BRANZ, 1998).

Building overheating is really an issue of the thermal comfort of the occupants. Thermal comfort of people depends on many factors, including (in order of importance): air temperature, mean radiant temperature, air velocity, humidity, clothing insulation and activity level (Olesen, 1993). Various indices of thermal comfort are available based on some or all of these parameters.

One measure of thermal comfort is the Effective Temperature (ET^*), defined as the temperature at 50% relative humidity that yields the same total heat loss for a person as for the actual environment (ASHRAE, 1993). The ASHRAE Comfort Zones are for ET^* between ambient temperatures of 20°C and 26°C. Another index places the comfort range at between 20°C and 25°C ambient temperature at 50% relative humidity. Above 25-26°C people become 'slightly warm', and above 30°C 'warm' (ASHRAE, 1993). The Comfort Zones indicate maximum comfortable ambient temperatures for lightly clothed, sedentary people.

There is limited information on the temperature conditions that New Zealanders find comfortable. As a first approximation the ASHRAE Comfort Zones are used here.

Humidity levels in New Zealand homes have been studied by BRANZ. A summary of the typical daily range of humidity appears in Table 18. During periods of summer overheating the humidity will tend to be at the lower end of the range, at just below 50%.

Table 18. Typical humidity range found in NZ homes (Cunningham, 1998).

	Unheated		**Heated**		
	Living Room	**Bedroom**	**Living Room**	**Bedroom**	**Average**
Summer	40-65%	50-70%	40-60%	45-70%	55%
Winter	50-75%	65-80%	40-70%	50-70%	65%

The actual temperature inside a building will differ from the external temperature for many reasons, including the thermal lag of the building, and solar and internal gains. At times of overheating the inside temperature will generally exceed the outside temperature, even if large amounts of ventilation are used. However, the actual difference between the internal and external temperature will vary widely for different house types, house layouts, operating modes and weather conditions.

For the purposes of estimating the increase in the incidence of overheating caused by climate change, it is assumed that the internal temperature always exceeds the external temperature, so that when the external temperature exceeds 25°C the internal temperature also exceeds 25°C, even if large amounts of ventilation are used, and thus the conditions would be outside ET*, the zone of thermal comfort.

The temperatures adopted for the neutral or comfortable temperature range for this study are a 'comfortable range' of 20-25°C, a 'slightly uncomfortable' range of 25-30°C, and a 'uncomfortable' range of greater than 30°C.

Analysis of the climate change scenarios provided the number of days per year that these threshold temperatures are exceeded, and are listed in Table 19, (see also section 18.4, page 91). There are dramatic increases for Auckland and Christchurch, and potentially significant increases for Wellington and Invercargill. It appears that regions that already have high summer temperatures, such as Auckland and Christchurch, have the greatest absolute increase in summer overheating.

The increases in Auckland and Christchurch are enough to create a summer ‘cooling season’ lasting a month or more. This level of prolonged discomfort is unlikely to be tolerated by most homeowners, who would be forced to take mitigation measures. If householders respond to climate change induced increased overheating by the use of air-conditioners, the result would be an increase of GHG emission, setting up a positive feedback loop. This is clearly an undesirable consequence, and emphasises the importance of good solar design features.

Not all houses will be equally affected by overheating. Those houses with good solar design features, such as properly shaded North facing windows, minimal West windows, or provision for effective passive ventilation, should be least affected. Houses without such features could suffer severe overheating. Thermal mass can be used to reduce the fluctuations in temperature by making the house slow to heat up and slow to cool down, and is best utilised in conjunction with good solar design.

The change in air-conditioning load has not been quantified, as only a few percent of houses nationwide currently use air-conditioners (Roussouw, 1997). In the next year’s research it is planned to quantify the change in air-conditioning load for office buildings.

Table 19. Number of days per year with maximum temperature exceeding 25°C.

	Now	**2030**	**2070**
Auckland	20	25-37	31-81
Wellington	3	4-7	5-21
Christchurch	26	29-36	32-64
Invercargill	2	2-3	3-11

10. EFFECTS ON CLIMATE CHANGE OF CONSTRUCTION

In this section those aspects of the construction industry and housing likely to affect the extent of climate change are examined.

Life Cycle Analysis (LCA) methods can be used to quantify the life time environmental impacts of buildings. The building life cycle extends from construction (including resource extraction and manufacturing), through occupancy (including energy use, maintenance and refurbishment), to demolition. Some issues often considered in LCA studies include (SETAC, 1993):

1. Raw materials extraction
2. Processing
3. Transportation
4. Energy use
5. Atmospheric emissions
6. Water emissions
7. Solid waste

Two methods for LCA type evaluation of buildings are ATHENA™ (Cole et al., 1996) and The Office Toolkit (Bishop, Durrant, and Bartlett, 1995). These assessments are very comprehensive, and only some of the issues assessed are relevant to climate change. The most important one being the greenhouse gas emissions at the various stages of extraction, processing, manufacture, occupancy (including energy use), and demolition. Some aspects of building design and form that affect the amount of greenhouse gas (GHG) emissions are also considered in these evaluations. These tools have not yet been adapted for use in New Zealand.

In terms of climate change, the most important impact of houses is GHG emissions.

Buildings release GHGs at all stages of their life. There are many different GHGs, and buildings emit most of them. It is important to know what GHGs are emitted, at what stage of the house’s life, and in what quantities. Different GHGs make different contributions to climate change, rated by their Global Warming Potential (GWP). For example, the GWP of methane is 21 times that of carbon dioxide, measured at a 100-year time scale.

In this section the GHGs emitted from houses are examined briefly to rank their importance. Then GHG emission factors for various types of space and water heating are calculated so that the actual GHG emissions from these sources can be calculated. The change in GHG emissions with climate change is calculated for some house types and appliances. Finally, some aspects of building design and operation that can affect the amount of GHG emissions are discussed.

10.1 What GHGs are Emitted from Houses

The emission of GHGs from houses is examined in this section to determine which gases are a significant proportion of the total life-cycle emissions for houses.

CO_2 - Carbon Dioxide

Up to 73% of energy use during a building's NZBC 50-year life comes during occupation, and the remainder for manufacture, construction and demolition (Jaques et al, 1997). Similar proportions were found for manufacture versus occupancy CO_2 emissions from a typical house by Honey and Buchanan (1992). Significant amounts of CO_2 are released during the manufacture of building materials, especially if concrete and steel are the primary structural elements. Occupancy emissions can be reduced by using good thermal design and efficient appliances, perhaps reducing emissions by a larger net amount and more cheaply than by changing construction materials.

N_2O - Nitrogen Oxide

N_2O is released primarily from diesel and petrol vehicles operated during construction and demolition. Other sources include fossil fuel boilers and generators. The impact of N_2O is much smaller than for CO_2: N_2O has less than 2% of the CO_2 Global Warming Potential (GWP) of fossil fuels in industrial use, and less than 1% for transport and most other fossil fuel uses (derived from information from the Ministry of Commerce (1997)). Therefore the N_2O emissions are negligible compared to CO_2 emissions for fossil fuel used from transport, heating, or generators.

CH_4 - Methane

Methane is released during the extraction and processing of fossil fuels, and in their combustion. Sources of methane for construction will be in transport, manufacturing processes using fossil fuel or thermal electricity, and occupancy. The CH_4 GWP for most processes are much less than 1% of the CO_2 GWP, except for residential combustion of coal and wood, where the GWP is about 10% due to gasification of wood and coal and incomplete combustion (Ministry of Commerce, 1997).

CFCs - Chloroflurocarbons

CFCs have been used in the past for a variety of building components including insulation and air-conditioning. As older buildings containing CFCs age and are refurbished or demolished, there is the potential for their release into the environment. CFCs from air-conditioners are being actively recycled or destroyed, though few houses have air-conditioning installed (Roussouw, 1997). CFCs contained in polystyrene or similar products will be released slowly during the life of the building.

New Zealand made expanded and extruded polystyrene (EPS) products have never used CFCs or HCFCs as blowing agents, using pentane instead (PINZ, 1998). Products containing CFCs (e.g. extruded polystyrene) might have been imported into New Zealand, though probably in small amounts. Polystyrene insulation has been used in quantity in only a small percentage of New Zealand homes, and much of that is blown with CO_2, pentane or similar compounds, so the GHG contribution from this source is likely to be very small. About 11% of new homes in the June 1998 quarter in New Zealand used polystyrene based cladding systems. The author only has anecdotal information on the prevalence of polystyrene insulation in existing New Zealand houses.

CFC use has been restricted worldwide with substitution by HCFCs, CO_2, or gases such as pentane or ammonia. CFCs are no longer imported in bulk into New Zealand, only in finished products like refrigerators. HCFCs are less potent greenhouse gases than CFCs, mainly because of their lesser lifetime in the atmosphere. However, the greenhouse warming contribution of HCFCs will continue to grow as their use increases (Houghton et al, 1996).

PFCs - Perfluorocarbons

Perfluorocarbons (PFCs) are extremely potent greenhouse gases[v], emitted mainly during aluminium refining. Total PFC emissions for New Zealand (of which aluminium refining is the primary source) were estimated by the Ministry for the Environment (1998) at 249 kT CO_2 equivalent. Dividing by the gross production of approximately 285,000 t gives an emission factor of approximately 0.9 t CO_2 eq /t Al. This is in addition to the other GHG emissions, including 2.0 kg CO_2/kg Al for aluminium production (Ministry of Commerce, 1997). Thus the total emission of GHGs for aluminium production will be approximately 2.8 kg CO_2 eq./kg Al. Emissions of PFCs from aluminium joinery in a house (containing about 250 kg of aluminium) could be 225 kg CO_2 eq., if there is no recycled content, which is 0.5-3% of the total construction GHG emissions (Buchanan and Honey, 1994). Thus PFCs might contribute 0-1% of lifetime GHG emissions of a house.

Conclusion

In conclusion, the most significant greenhouse gases for houses are CO_2, PFCs, CFCs, HCFCs, and N_2O. The contribution of N_2O is small relative to the CO_2 emissions and can be ignored. CFC and HCFC emissions are expected to be near zero for most houses. PFC emissions for the smelting of aluminium used in a house are small, at maybe 0-1% of life-time GHG emissions. Most of the GHG emissions arise from energy use during occupancy, and the construction emissions are mainly CO_2. The lifetime GHG emissions from houses are almost entirely from CO_2 during occupancy, most of which arise from energy use.

10.2 Energy GHG Emissions

The predominate energy sources for house heating in New Zealand are electricity, natural gas, LPG, coal, diesel and wood (Roussouw, 1997), which have a range of GHG emissions per unit of delivered heat because of the different carbon content of the fuel, and the distribution and appliance efficiency. Emission factors for the major greenhouse gases for home heating fuels are calculated in this section. They are then combined with heater efficiencies to calculate the GHG emissions for various heating types.

10.2.1 Electricity greenhouse gas emissions

New Zealand's electricity is generated by hydro, thermal, and geothermal power stations. In 1996 the percentages of total electricity supply were 79%, 14%, and 6% respectively (Ministry of Commerce, 1997). This provides a 'snapshot' of the current mix of electricity generation. As the generating plant changes, and the pattern of energy use changes, these figures will change, as will the GHG emissions.

As the hydro-power stations have very low emissions the average GHG emission for New Zealand electricity is very low by international standards. Currently, low emission hydro-power meets about 75-80% of New Zealand's electricity needs, however this does not fully meet the baseload so thermal stations are also used (Ministry for the Environment, 1990). Any increase or decrease in electricity consumption is therefore usually met by thermal stations, with associated high CO_2 emissions. Demand for electricity has grown enough in the last few years that the marginal generation is almost always from thermal stations at any time of day or time of year (Lermitt, 1998).

In this section the GHG emissions per kWh of electricity are derived from figures in the "New Zealand Energy Greenhouse Gas Emissions 1990-1996" report (Ministry of Commerce, 1997).

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[v] The GWP of PFCs range from 6,500 - 9,200 times that of CO_2, and are as potent as the worst CFCs.

Table 20. Summary of electricity generation by fuel type for 1996 fiscal year (from Ministry of Commerce (1997)).

Fuel Type	GWh	PJ	CO_2 emission (kt)	CO_2 emission per unit electricity (kg/kWh)	% of total generation
Hydro	28,004	100.8	NA	NA	78.7
Gas	4,312	15.5	2,442	0.57	12.1
Geothermal	2,001	7.2	297	0.15	5.7
Coal	438	1.6	561	1.28	1.2
Oil	61	0.2	NA	NA	0.2
Others[1]	739	2.7	NA	NA	2.1
Total	**35,555**	**128**	**3,300**	**0.09**	**100**

[1] Includes electricity generation from biogas, industrial waste, wood, and wind.

Table 21. GHG energy emission factors (t/PJ) (from Ministry of Commerce (1997)).

	CO_2	CH_4	N_2O	NO_x	CO	NMVOCs
Gas	52,605	2.7	0.09	198	28.8	4.50
Liquid Fuel[1]	60,000	0.9	0.3	200	15	4.75
Coal	93,000	0.7	1.5	361	8.6	4.75

[1] Approximate only as a mix of residual and distillate fuel oil.

Table 22. Thermal electricity generation greenhouse gas emissions (t) (from Ministry of Commerce (1997)).

Year	CO_2	CH_4	N_2O	NO_x	CO	NMVOCs
1990	3,518,000	159	13.1	13,200	1680	280
1991	3,912,000	192	10.0	14,600	2010	320
1992[vi]	5,065,000	214	22.3	18,800	2270	400
1993	4,099,000	193	13.4	15,400	2030	330
1994	3,265,000	153	11.2	12,300	1610	270
1995	2,952,000	130	13.2	11,200	1370	230
1996	3,746,000	168	15.3	14,200	1770	300

Table 23. Electricity generation greenhouse gas emissions/ GWh electricity (t/GWh).

Year	CO_2	CH_4	N_2O	NO_x	CO	NMVOCs
1994	95.8	0.0045	0.00033	0.36	0.047	0.0079
1995	83.6	0.0037	0.00037	0.32	0.039	0.0065
1996	103.6	0.0046	0.00042	0.39	0.049	0.0083
Average	94.3	0.0043	0.00038	0.36	0.045	0.0076

Table 24. Global warming potentials (GWP) for various gases (from IPCC (1996)). Units of kg CO_2 equivalent.

Year[vii]	CO_2	CH_4	N_2O	NO_x	CO	NMVOCs
20	1	56	280	-	-	-
100	1	21	310	-	-	-
500	1	6.5	170	-	-	-

Taking the GWP from Table 24, and multiplying by the emissions of each gas in Table 23, gives the GWP in units of CO_2 equivalent. These are expressed as a percentage of the total GWP in Table 25, page 58, to show the relative importance of each greenhouse gas. As almost all the GWP for electricity generation arises from CO_2, the contributions of the other GHGs can be ignored.

[vi] There was a large jump in 1992 in thermal electricity generation, and hence GHG emissions, because of low hydro lake levels.

[vii] The GWP varies depending on the time scale used, as the GHGs have different lifetimes in the atmosphere. Time scales of 20, 100, and 500 years are given. The 100-year time scale is the one used most commonly.

Table 25. Contribution of GHGs to the net GWP of electricity generation.

Year	CO_2	CH_4	N_2O	NO_x	CO	NMVOCs
20	99.6%	0.3%	0.1%	0%	0%	0%
100	99.8%	0.1%	0.1%	0%	0%	0%
500	99.9%	0.0%	0.1%	0%	0%	0%

From Table 23, page 57, the CO_2 emissions per GWh electricity are about 95 t/GWh, or 0.095 kg CO_2/ kWh. Rounding to 0.1 kg CO_2/ kWh is reasonable as the emissions vary from year to year with the amount of hydro power generated, and are likely to increase with increased thermal generation.

The emissions factors for thermal electricity using gas and coal are 0.57 kg CO_2/ kWh and 1.28 kg CO_2/ kWh respectively (from Table 20, page 56). Gas generation outweighs coal generation by 10:1, so the combined emission factor is the weighted average of gas and coal emissions, and is 0.64 kg CO_2/ kWh.

In summary, CO_2 is the predominate GHG emitted by electricity generation. The emission factor for 'average' national electricity is about 0.1 kg CO_2/kWh, depending on the amount of available hydro generation capacity. The emission factor for thermal electricity is about 0.64 kg CO_2/kWh. These figures are used in the subsequent sections to estimate the CO_2 emissions for electricity use for space and water heating.

10.2.2 Fossil fuel greenhouse gas emissions

In this section the GHG emissions for direct use of fossil fuels for heating are derived. The GHG emissions for each fuel type used in residential heating are given in Table 26. These are slightly different from the figures in Table 21, page 56 as the heating appliances have a different performance from thermal power stations. These are converted to units of GWP in

Table 27. The GWP is almost entirely due to the CO_2 emissions for all fuels except for coal where the CH_4 proportion is significant. At a 100-year time scale the total GWP for coal is 1.07 times the GWP caused by CO_2, so this factor will be used to scale the CO_2 emissions for coal. Table 28, page 60 displays these figures converted to more convenient units of kg CO_2/kWh. The emission factors range by almost a factor of 2 from 0.19 kg CO_2/kWh for natural gas, to 0.36 kg CO_2/kWh for coal.

Table 26. GHG EMISSION FACTORS in t/PJ for several home heating fuels (from Ministry of Commerce (1997)).

Fuel	CO_2	CH_4	N_2O	NO_x	CO	NMVOCs
Coal	92,100	285	1.3	219	456	190
CNG	52,600	0.9	0.1	42	9	4.5
LPG	60,400	1	0.6	45	10	4.8
Fuel Oil	73,700	0.7	0.6	62	15	4.8

Table 27. GHG GWP in equivalent CO_2 units (t/PJ). Percentages are the proportion of total GWP for each GHG.

Fuel	Year	CO_2	CH_4	N_2O	Total	CO_2	CH_4	N_2O
Coal	20	92,100	15,960	364	108,424	84.9%	14.7%	0.3%
	100	92,100	5,985	403	98,488	93.5%	6.1%	0.4%
	500	92,100	1,853	221	94,174	97.8%	2.0%	0.2%
Natural Gas	20	52,600	50	28	52,678	99.9%	0.1%	0.1%
	100	52,600	19	31	52,650	99.9%	0.0%	0.1%
	500	52,600	6	17	52,623	100.0%	0.0%	0.0%
LPG	20	60,400	56	168	60,624	99.6%	0.1%	0.3%
	100	60,400	21	186	60,607	99.7%	0.0%	0.3%
	500	60,400	7	102	60,509	99.8%	0.0%	0.2%
Diesel	20	68,700	39	168	68,907	99.7%	0.1%	0.2%
	100	68,700	15	186	68,901	99.7%	0.0%	0.3%
	500	68,700	5	102	68,807	99.8%	0.0%	0.1%

Table 28. Emission factors for several fuel types for residential use.

	Emission Factor kg CO_2 equivalent/kWh
Coal	0.36
Natural Gas	0.19
LPG	0.22
Diesel	0.25
Electricity	0.1
Marginal Electricity	0.64

10.3 GHG Emissions Factors for Space Heaters

GHG emissions for home heating can now be calculated using the emission factors from the previous sections and the efficiencies of individual heating appliances. The calculation method is as follows:

Emission (kg CO_2 equiv./ kWh) = Energy Emission Factor / Appliance Efficiency

The method is similar to that used in the BREAM Environmental Standard (Prior and Bartlett, 1995). These calculations have been carried out for common heating appliance types used in New Zealand and are presented in Table 29, page 62, and Figure 4, page 63.

Key assumptions made to develop Table 29 and Figure 4 are:

1. Electricity emission factors are for thermal generation, as heating generally occurs during peak times.

2. Emission factors for night store electric heaters are the national average, as they operate outside of peak times.

3. Coal emission factors are for national average coal, as local factors will vary.

Wood has not been considered for this analysis for several reasons. Wood is a natural product, so the embodied carbon was recently absorbed from the atmosphere – international rules for GHG emissions of wood have yet to be formulated. Figures for the GHG emissions for wood production are not readily available, and would vary widely from place to place depending on the source of the wood (e.g. virgin, waste or recycled) and the management, processing and transportation practices.

Non-fossil fuel energy sources (such as solar, wind, biomass) have also not been considered. Their GHG emissions are likely to be very low (or possibly negative for biomass). Widespread use of such energy sources could significantly reduce New Zealands GHG emissions.

The lowest emission heater types are the gas appliances. This result rests heavily on the assumption that electricity is assigned the the marginal CO_2 emissions of the thermal stations. Coal attracts high emissions, even for the most efficient burners. Electric heat pump appliances have quite low emissions, because for every unit of electricity they produce more than 1 unit of heat.

Using fossil fuels directly for heating produces less GHG emissions than the same amount of delivered heat from electricity generated by thermal power stations. Widespread substitution of electricity by natural gas or other fuel for house heating could lead to nationwide reductions in heating GHG emissions as the peak evening electricity load in winter (largely powered by thermal stations) would be reduced.

Table 29. Space heating appliance efficiencies and greenhouse gas emissions (efficiency data from Roussouw (1997)) [viii]**.**

Fuel	Heater Type	Fuel Emission Factor (kg CO_2 eq. /kWh)	Efficiency (%)	kg CO_2 equivalent / kWh heating output
Electricity	Air conditioner	0.64	190	0.34
Electricity	Ducted heat pump	0.64	168	0.38
Electricity	Resistance	0.64	100	0.64
Electricity	Floor	0.64	90	0.71
Electricity	Night store	0.09-0.64	80	0.12-0.80
Electricity	Ceiling	0.64	60	1.07
Natural gas	Unflued	0.19	81	0.23
Natural gas	Flued	0.19	80	0.24
Natural gas	Central heating	0.19	66	0.29
LPG	Unflued	0.22	81	0.23
LPG	Flued	0.22	80	0.24
LPG	Central heating	0.22	66	0.29
Diesel	Central heating	0.25	42	0.59
Coal	High eff. double burner	0.36	80	0.44
Coal	Basic double burner	0.36	65	0.55
Coal	Pot belly	0.36	35	1.01
Coal	Free-standing metal fire	0.36	25	1.42
Coal	Open fire	0.36	15	2.37

[viii] The night store low figure of 0.12 is calculated assuming the average electricity emission factor of 0.1 kg CO_2/kWh as at night there is less reliance on thermal power stations. The night store high figure of 0.80 is for thermal electricity.

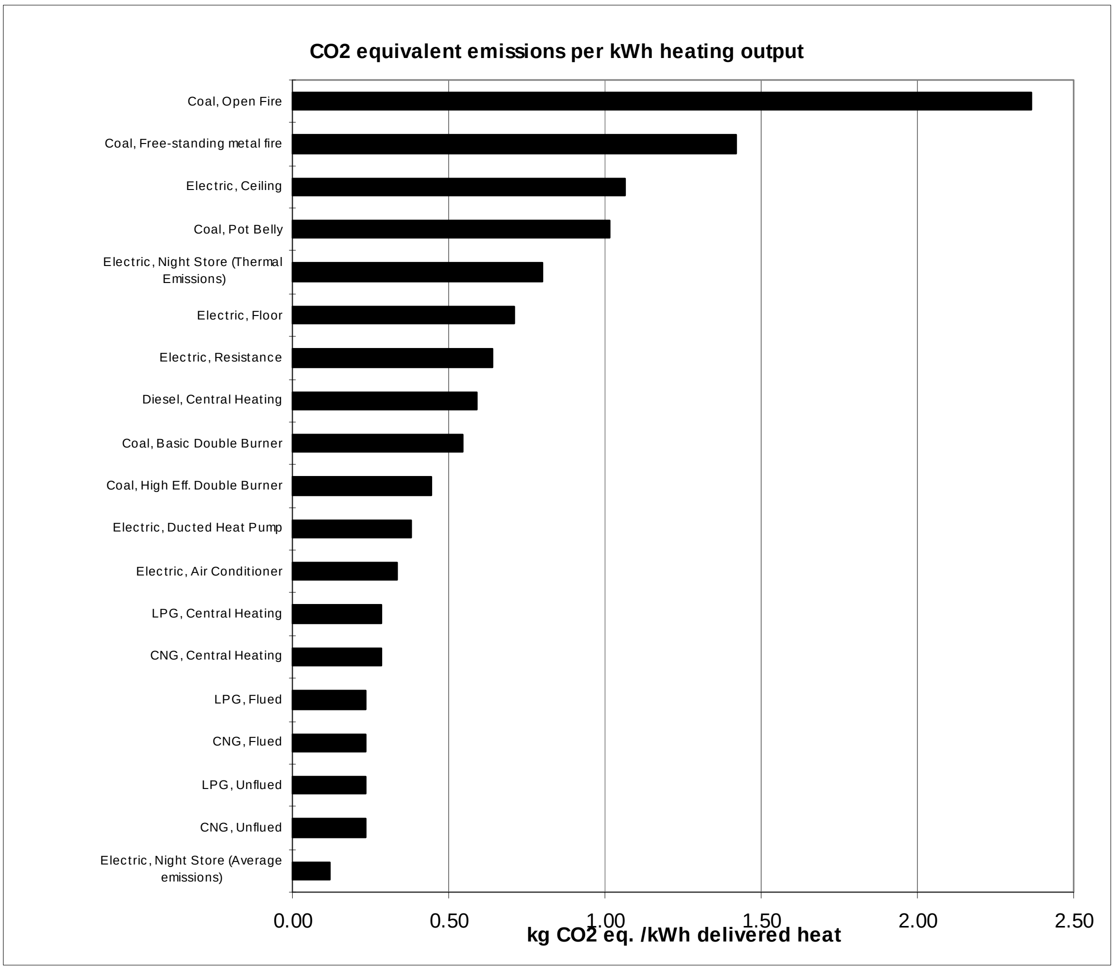

Figure 4. Space heating appliance GHG emissions.

10.4 GHG Emission Factors for Hot Water Heaters

The GHG emission factors for hot water heaters are calculated in a similar fashion to those for space heating. They range from 0.11 to 1.08, a factor of 10 times, from lowest to highest (Table 30).

Table 30. GHG emission factors for hot water heaters (efficiency data from Roussouw (1997)).

Appliance type	Efficiency	GHG Emission factor (kg CO_2/ kWh delivered heat)
Electric night store, grade a[ix]	86%	0.11-0.74
Electric heat pump	300%	0.21
Electric solar	250%	0.26
Electric instant	95%	0.67
Electric boiler	90%	0.71
Electric cylinder grade a	86%	0.74
Electric cylinder grade b	82%	0.78
Electric cylinder grade c	74%	0.86
Electric cylinder grade d	70%	0.91
Gas solar	200%	0.09
Gas condensing	80%	0.24
Gas instant ‘5 star’	66%	0.29
Gas cylinder ‘4 star’	58%	0.33
Gas cylinder ‘3 star’	55%	0.34
Gas cylinder ‘2 star’	51%	0.37
Gas cylinder ‘1 star’	46%	0.41
Coal wetback	33%	1.08
Fuel oil boiler	65%	0.38

[ix] See footnote viii.

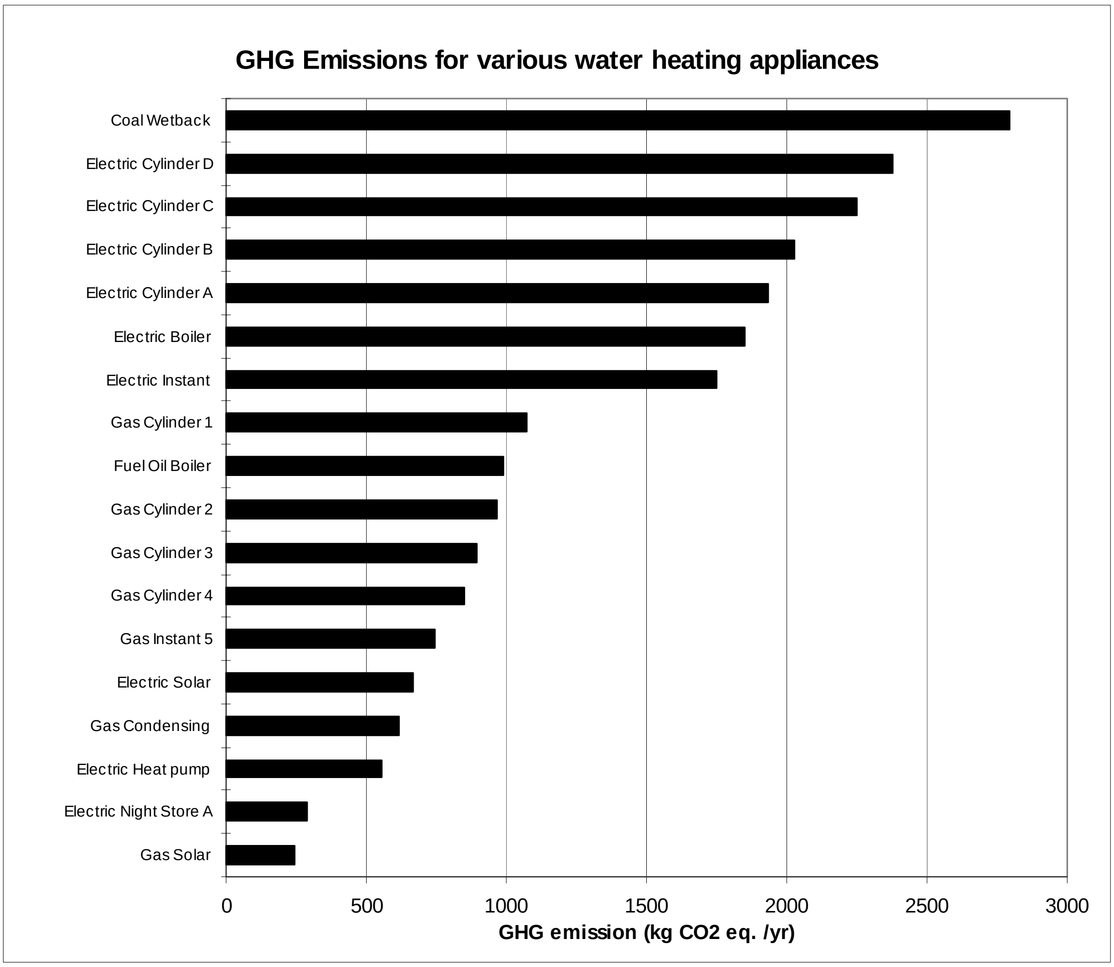

Figure 5. Hot water heating appliance GHG emissions.

10.5 GHG Emission Reductions for Heating with Climate Change

Increased environment temperatures will reduce the required heating energy, which in turn will result in reductions in GHG emissions. All things being equal, the percentage reduction in heating GHG emissions will be the same as the percentage reduction in heating energy (see Table 16, page 49, and Table 17, page 50 for reductions in heating energy).

However, the actual GHG emission reductions will depend on the space heating requirement and the heating appliance. GHG figures have already been given for space heating (Table 16, page 49), assuming an emission factor of 0.64 kg/kWh for an electric resistance heater using thermal electricity. These are expressed as reductions from the base 1990 climate, summarised in Table 31, page 66. These can be scaled to match individual heating appliances by using the appropriate emission factors in Table 29, page 62. For example, if the heating source was flued natural gas, multiply the reductions in GHG emissions in Table 31, page 66 by 0.23/0.64.

GHG emission reduction have been calculated for other building types and heating schedules by:

- Calculating the yearly heating energy under the current climate.
- Finding the resultant climate change reduction in heating using the percentages in Table 16, page 49.

- Multiplying by the appropriate emission factor from Table 29 page 62.

Table 31 shows these calculated reductions in annual GHG emissions for space heating of a low mass insulated house, heated in the morning and evening to 18°C, assuming emissions of 0.64 kg/kWh (electric resistance heater using thermal electricity).

Table 31. Reductions in annual GHG emissions for space heating.

	Reduction in GHG by 2030 (kg eq CO_2)	**Reduction in GHG by 2070 (kg eq CO_2)**
Auckland	115-837	809-1000
Wellington	673-899	781-2383
Christchurch	132-451	282-2022
Invercargill	665-1068	867-2908

Reductions in emissions from water heating can be calculated by using the percentage reductions from Table 17, page 50, multiplied by the assumed yearly consumption of 2600 kWh per household per year as used by Roussouw (1997), and multiplied by the appropriate emission factor from Table 30, page 64. An example using an A grade electric hot water cylinder using thermal electricity (emission factor of 0.74 kWh) is given in Table 32. The reductions in hot water heating GHG emissions are much smaller than the reductions for space heating emissions.

Table 32. Reductions in yearly household GHG emissions for water heating. Units of kg CO_2 equivalent.

2030, Low	15
2030, High	54
2070, Low	35
2070, High	154

In summary, reductions in space heating with climate change may be larger, leading to large reductions in GHG emissions from houses. Reductions in hot water heating emissions (assuming constant demand) will be much smaller, though significant on a national scale.

10.6 Energy and Resource Efficiency

The form, construction type, and location of a building can strongly influence the behaviour of occupants, and consequently their energy and resource demands (Polster et al, 1996). For example a well insulated building will consume less heating energy than a poorly insulated building for the same level of service. The BREEAM Environmental Standard (Prior and Bartlett, 1995) and the BRANZ Green Home Scheme (BRANZ, 1997) focus on the building design stage, as this is where the greatest improvements in building efficiency can be achieved at lowest cost, and they are effective for the life of the building.

The choice of materials at the design stage has a direct influence on the greenhouse gas emissions at both the construction and occupancy stages. Timber buildings would generally have lower construction GHG emissions than concrete buildings (Penttala, 1997), whereas high thermal mass houses can require less energy to heat than similarly insulated low thermal mass houses (Pollard and Stoecklein, 1997). However, thermal mass in the form of concrete has a large associated CO_2 emission during manufacture.

Net lifetime energy GHG emissions could be reduced by using much higher levels of insulation than normal. A study in England has shown that the optimum insulation thickness (in terms of total life time CO_2 emissions) is 34 cm for cavity walls (Lowe, Sturges, and Hodgson, 1997). The shorter heating season, lower heating demands, and greater use of low CO_2 emission electricity for New Zealand houses, means that the 'breakeven' point (where the emissions for producing extra insulation outweigh the savings in energy emissions) will not be as large as 34 cm, but could well be greater than the proposed requirements of NZS 4218:1996. The current energy efficient standards NZS 4218:1996 are based on an economic optimum according to government rules, which results in the current proposal for insulation levels of R1.5 and R1.9 for walls, which can be achieved by 10 cm or less of insulation in a timber framed wall.

10.7 Building Locale and Transportation

For many New Zealand households, more greenhouse emissions come from cars used for personal transport than from energy use in the house. Driving a family car 5000 km per year will emit nearly 2000 kg of CO_2, compared to about 1000 kg for a typical household energy consumption of 10,000 kWh/year. Total mileage of more than 30,000 km annually for a household is not uncommon.

Electricity generation produces about 15% of New Zealand's total CO_2 emissions, compared to 44% for domestic transport (Ministry of Commerce, 1997). About 60% of transport energy is from petrol, much of which is used for personal transport. The remainder is used in the transport industry, a proportion of which is used directly or indirectly by the construction industry for hauling logs, trucking cement and aggregate etc.

These GHG emissions could be reduced by urban planning that encourages shorter commuting distances, public transport, and ride sharing.

11. COMPLIANCE COSTS

Possible carbon charges, and energy efficiency and waste reduction legislation would impose compliance costs onto the building industry. Costs could include measurement, auditing, legal, and actual direct resource charges or taxes. New Zealand Treasury (1997) forecasts are pessimistic about the costs of carbon reduction measures, anticipating large additional costs, though in overseas studies net savings from adopting energy efficiency measures are indicated (DOE, 1991); (Lovins and Lovins, 1997).

The New Zealand Government advocated GHG emissions trading at the Kyoto meeting (Minister for the Environment, 1997), partly because it expects that this will lead to the least cost for GHG reductions. This position is also favoured by many major New Zealand industries (GPC, 1998). If the initial success of the U.S. Acid Rain emissions trading programme (Dudeck et al, 1997) is repeated for GHG emissions trading, then the least cost position will be justified.

The New Zealand government has considered introducing a system of carbon taxes or emission permits. Both would impose additional costs to the production of new homes, and the operation and maintenance of all homes. In a study by the New Zealand Treasury, charges of \$100 and \$200 per tonne of carbon (equivalent to \$27 and \$54 per tonne CO_2) were used as a benchmark for examples (New Zealand Treasury, 1997). Based on calculations of net carbon emissions for the construction of a house by Honey and Buchanan (1992) the extra costs for carbon charges would be as follows:

Table 33. Cost of possible carbon charges for a new 94m² home.

Construction type	**Timber frame, weatherboard, concrete tile**	**Concrete floor, concrete block, steel roof**	**Concrete floor, brick veneer, steel roof**
House cost (1991 figures)	\$77,100	\$70,300	\$73,400
Carbon emission (t)	1.6	6.3	9.6
Carbon cost (timber stores)	\$160-\$320	\$630-\$1,260	\$960-\$1,920
Carbon cost (no storage)	\$440-\$880	\$810-\$1,620	\$1,040-2,080

The information used in Honey and Buchanan (1992) dates back to 1983 at least, and so is out of date in many aspects. The information is currently being updated, and it is anticipated that more accurate estimates can be made within a year or two.

This analysis rests heavily on the assumption that timber stores carbon, thereby offsetting the carbon emissions for other building components. It is not certain whether timber products will be given 'carbon-credit' for storing carbon.

The government's stated intent in imposing carbon charges is "to reduce CO_2 emissions in New Zealand by increasing the price of carbon, thereby changing people's behaviour" (New Zealand Treasury, 1997). Adding cost for carbon charges pre-supposes that the tax will be sufficient to favour the lower impact material. This is not always the case for buildings. For example, a concrete tile roof is currently more expensive than a corrugated steel roof, but the additional tax on the steel roof does not make the concrete roof a cheaper alternative (based on carbon emissions of Honey and Buchanan (1992) and roofing costs from Page (1997)). In this example, a carbon charge would not effect a change from a steel to concrete tile roof.

Table 34. Comparison of concrete tile vs. steel roof costs for a 94 m² home with and without carbon charges.

	No carbon charge	**Cost with carbon charge**	
		@ \$100/t	**@ \$200/t**
Concrete tile more expensive than steel by:	20%	18%	16%

A similar situation is likely to arise in wall types. Based on figures from Honey and Buchanan (1992) concrete block is cheaper than timber and weatherboard, with or without carbon charges.

Table 35. Comparison of wall costs for a 94 m² home with and without carbon charges.

	No carbon charge	Cost with carbon charge	
		@ $100/t	@ $200/t
Weatherboard more expensive than concrete by:	27%	24%	23%

Concrete slab floors recently have been 10-20% cheaper than a timber floor. Again, carbon charges would not force a change from concrete to timber.

According to the analysis of Honey and Buchanan (1992) the house with the lowest carbon emission was the most expensive: nearly $7,000 more than the common house construction, and nearly $4,000 more than the house with the highest emissions (Table 33, page 68). The carbon charges illustrated are unlikely to change consumer or builder choices.

The price signals sent by likely carbon charges are small, and could well be insufficient to precipitate a change to lower carbon emission building materials. The current cheapest building material is determined largely by the price in the international marketplace, which sends much stronger price signals than a local, low-level carbon charge. For example, timber prices have dropped recently following the economic downturn in Asia by a much greater amount than any likely carbon charges. Thus the carbon charges are unlikely to be enough to make the lowest carbon emission building materials the cheapest.

Carbon charges would also increase energy costs for homes. Assuming the net emissions of 0.095kg CO_2/kWh apply to electricity the price would rise by about 0.25c/kWh, a 2.5% increase. For LPG or CNG the price would rise about double this at 5%. Based on an average figure of 10,000kWh per year for a household, the additional cost would be $25-$50 per year. This level of price increase may be insufficient to stimulate reduced consumption, and would certainly not justify switching from electricity to gas for space or water heating, even though this would result in substantial CO_2 reductions for most households (refer to section 9 for details of CO_2 emissions for appliances). Savings in energy for space and water heating may offset most or all of any carbon charges in the long term (see Section 7, page 42, and Section 8, page 50).

Carbon charges would increase costs for the transportation and construction sectors (Steiner 1990).

Increases in rainfall and run-off of about 10% in hydro-catchment areas may increase the hydro-generating capacity, and better match it to seasonal demand (Mundy 1990), possibly reducing the overall cost of carbon charges on electricity.

Where the carbon taxes will have an effect is on the efficiency of power generation and manufacturing processes. For example, the electricity industry alone could be faced with a tax bill of $M90-180 per year for carbon emissions of 900,000 tonnes per year (see Table 20, page 56 for electricity CO_2 emissions for 1996). This is probably where the carbon charges are aimed.

The increased cost of cement from carbon charges may increase the amount of cement imported, a perverse result both in terms of CO_2 emissions and durability, as New Zealand cement is specially formulated for local conditions. This could happen for other building materials and components.

12. INLAND FLOODING

The high end 2070 climate change scenarios indicate possible large increases in rainfall, in many areas up to 15-40%. Clearly, significant impacts should be expected if these scenarios eventuate. If tropical cyclone activity increases then increases in extreme rainfall are likely to be far larger.

Climate models project that "changes in the spatial and temporal patterns of precipitation would occur" (Watson, Zinyowera, and Moss, 1996) though it is not possible at present to anticipate these changes with any confidence. In the words of the IPCC:

> "Warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects for more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events. Knowledge is currently insufficient to say whether there will be any changes in the occurrence or geographical distribution of severe storms, e.g. tropical cyclones." (Watson, Zinyowera, and Moss, 1996).

Some New Zealand research has anticipated an increase in tropical cyclones in the north of New Zealand (Salinger 1990).

12.1 Extent of Flooding Risk

Flooding is a major cause of building damage in New Zealand. The 13 major floods between 1968 and 1981 are estimated by Ericksen (1985) to have caused $1.75 billion damage (1984 dollars). Some major population centres are guarded by substantial flood protection works, notably Thames, the Hutt Valley, and Christchurch. In Christchurch alone more than 140km^2 of urban areas containing $15 billion dollars of property are protected (1988 dollars) (McKerchar and Pearson, 1989). In the Hutt Valley a 1 in 1000 year flood would directly affect 16,000 homes and commercial buildings (Wellington Regional Council, 1996). A large number of communities are built in flood-plains, low lying areas, or in proximity to flood-prone rivers. Ericksen (1985) reported that nearly 100 communities in New Zealand are flood prone, housing over 1.64 million people, of which on average about 20% are exposed to direct flood risk. Most of these communities were established long before the current flooding risk requirements came into force in the NZBC, or before the flooding risk was understood, with some homes flooded by only 1 in 20 year return period floods.

Clearly, many houses and communities are already subject to a level of risk that is unacceptable according to the current NZBC: any decrease in flooding return period could have dire consequences for these houses. For example, about half of the houses in Paeroa were flooded in 1981 by a flood with a 70-year return period (Ericksen, 1985). A 4-fold reduction in return period would increase the risk to about 60% in 10 years, roughly 1 flood per decade.

Clearly, any change in flooding that renders the established flood protection inadequate has the potential to cause vast damage.

Inland flooding is not confined just to houses near rivers: urban drainage systems can cause flooding when they are blocked or otherwise incapable of dealing with heavy rain. Drains that have outlets to flood-protected rivers are often mechanically closed when floodwaters rise, potentially causing flooding in areas well elevated from the river (Wellington Regional Council, 1996). The flow rates of urban drains are strictly limited: exceed them and flooding is sure to occur. As drains are designed to handle current extreme rainfall, they are liable to become overburdened more frequently as rainfall return periods decrease. In areas where all drains are designed to cope with the same extreme event there could be large scale catastrophic failure when this design level is exceeded.

12.2 Likely Changes in Flood Return Period

Relating changes in annual precipitation or extreme rainfall to the incidence and severity of flooding events is difficult as flooding hydrology is extremely complex.

Minnery and Smith (1996) were unable to come to any firm conclusion on changes in flooding other than the statement that the return period of the 1-in-100-year flood was likely to decrease substantially in a warmer climate, as a consequence of increased heavy rainfall events. In Section 18.6, it is noted that the regional pattern of the annual flood probabilities resembled the distribution of annual rainfall, and that changes in annual rainfall from the climate change scenarios might be used as a proxy measure of the changes in annual flooding. This procedure was used by Minnery and Smith (1996), who assumed that since the return period for heavy rainfall would reduce four-fold with a doubling of CO_2, the flooding return periods were reduced four-fold. In discussions with the author, NIWA hydrologists would not agree that changes in rainfall return period would necessarily lead to changes in flooding return period. That such recognised authorities are only able to come to general conclusions indicates the limited extent of scientific knowledge in this area, and the complexity of flooding hydrology.

An analysis of changes in river flood return periods with climate change was carried out for the Hutt River in Wellington (Leong, Jordan, and Ibbitt, 1992). They increased the rainfall intensity from historic storms arbitrarily by 5%, 10%, and 15%, and then used a sophisticated hydrological model of the catchment to determine what flood flow would result. In this way they were able to recalculate the flood return periods for climate change. Decreases in flood return period were by a factor of 3-4 for a 15% increase in rainfall. Fortunately for the Hutt Valley, current scenarios of rainfall indicated the Wellington region to have net decreases in rainfall. However, the intensity of individual storms is still expected to increase, so increased flooding is still a possibility.

Table 36. Changes in Hutt river flood return period with increases in rainfall (after Leong, Jordan, and Ibbitt (1992)).

	Increase in rainfall		
	5%	10%	15%
Return period (yrs)	New Return Period		
1000	580	360	230
500	300	190	130
200	130	85	59
100	66	46	33
50	34	25	18
20	14	11	9
10	8	6	5
5	4	3.3	2.8

In a recent unpublished paper, Smith (1998) attempted to convert changes in rainfall to changes in flooding without the arbitrary scaling described previously. He used a stochastic weather generator to provide rainfall 'input' for a flood model in Australia. The work was only possible because there were existing models of urban runoff and building flood damage, and detailed records of buildings. It is unlikely that this assessment could be replicated in New Zealand without major new research initiatives, requiring at the least:

1. A suitable stochastic weather generator
2. Detailed building information over entire catchments
3. A sophisticated urban hydrology/flooding model
4. A model of flood damage based on building characteristics (not available).

Any analysis would be specific to one catchment only, and would require significant effort to adapt to a new area.

The author is unaware of any current or proposed research programmes for New Zealand that could lead to significant progress in this area. It is not possible at this stage to quantify the change in inland flooding risk or damage with climate change beyond the crude statement that changes in the flooding return period match those of rainfall return period. Some recent Australian work of highlights the importance of climate change for flooding, and gives some possible directions for future research.

Scenarios for New Zealand are:

2030: No change through to a halving of the return period of flooding.

2070: No change through to a fourfold reduction in the return period of flooding.

As noted in section 6, page 34, a four-fold reduction in the 1 in 50-year flood (2% AEP) is not detectable over a 50-year period. So even if the high end of these reductions in flooding return period occur, it might be only in the closing years of the 21st century that they could be confirmed for a given catchment area.

12.3 Increase in Flooding Damage

Minnery and Smith (1996) described an assessment of changes in urban flood damage with climate change. They found increases in damage in already flood-prone areas were up to 10 times in the most susceptible catchments when the flood return periods decreased by a factor of three to four times. The increases in damage were much larger than the decreases in the return period, as there are defined thresholds (the 1 in 100-year hazard line) beyond which large numbers of homes become damaged by flooding. Ericksen (1985) has shown that flood losses in New Zealand continued to rise even after substantial flood protection works, as people were effectively encouraged to build behind the flood protection, even though they are only protected for flooding up to a certain level. Once this level is exceeded the damage can be enormous. With climate change, the ‘safety factor’ offered by current flood protection works may be reduced significantly, possibly leading to large increases in flooding damage. This provides a warning for buildings ‘sheltered’ behind hazard lines or flood protection measures: they are designed for current risks, and may fail catastrophically if the flooding return periods increase.

12.4 Minor Flooding: Guttering and Drainage

The Acceptable Solution for The NZBC Clause E1: “Surface Water” contains methods for designing drainage systems to cope with current rainfall extremes (BIA 1995). These are related to extreme rainfall return periods. For example, the minimum size of guttering and downpipes is determined by the roof size, roof pitch, and the expected extreme 10 minute rainfall that has a 10% AEP. Increases in the total annual amount of rainfall are unlikely to cause problems with roof drainage systems, but changes in the incidence of extreme rainfall may well increase the likelihood that drainage systems overload. Depending on the design of the system this may be just a nuisance, or could cause flooding of the ceiling or wall cavity.

If changes in rainfall increase the AEPs, then slight increases in the rainfall intensity would be expected. A doubling of the AEP for the 10 minute, 10% AEP rainfall would increase the rainfall intensity by about 5-25%, depending on the site, whilst a four-fold increase in the AEP would give increases of about 10-50% (Coulter and Hessell, 1980). Most houses should be able to cope with increases of this size with little problem. Those houses that currently have problems, or have drainage precisely matched to the current extreme rainfall may have increasing problems.

12.5 Landslips

Landslips occur most often and most severely during heavy, prolonged rainfall. For example, in the 1996/97 year the Earthquake Commission paid out an average of $4,200 on 704 claims for landslips causing damage to property (EQC, 1998). The majority of these occurred during cyclone Drena, and two other weaker cyclones that hit the Northland, Auckland, and the Bay of Plenty regions (Figure 6, page 74). Clearly, any decrease in rainfall return period, or increase in cyclone activity, is likely to increase the incidence of landslips. Quantifying this is practically impossible on a national or regional scale, as landslips are a highly localised event, affected by many continuously changing variables. In general, it could only be anticipated that areas with the largest increases in rainfall are likely to have the largest increases in landslips.

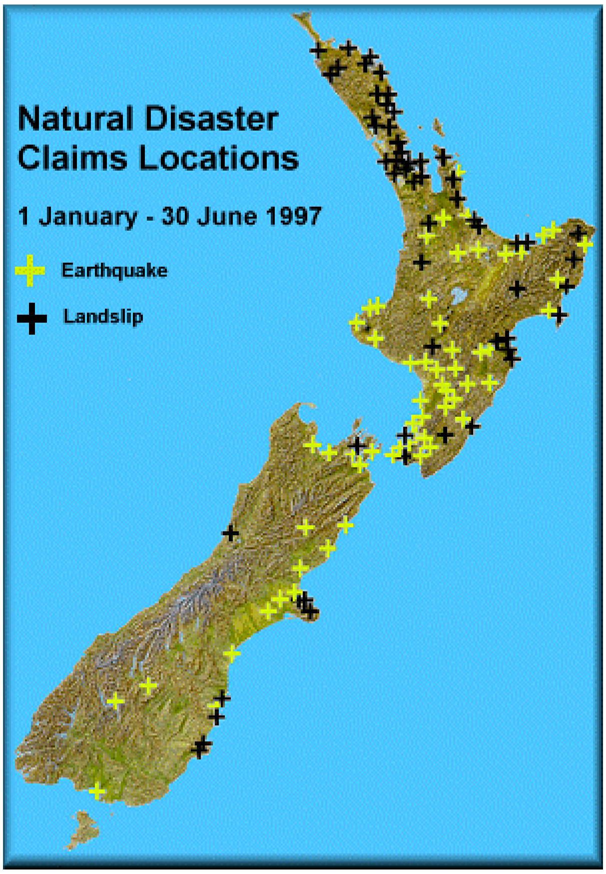

Figure 6. Locations of claims for landslip and earthquake damage (copied from EQC (1998)).

13. COASTAL FLOODING

Coastal flooding is a complex phenomenon, involving interactions between tides, estuaries, waves and wind, rain, air pressure and coastlines. Sea level rise is only one component of coastal flooding, albeit a major one. Changes in sea level will only equal changes in hazard lines if these other factors and their interactions are unchanged by climate change. However, as the sea level rise is the easiest to deal with, and is the only factor that can be predicted with any reliability by current climate change models, it will be used as the basis for analysis.

Problems caused by sea level rise are not necessarily restricted to shore-line sites. Storm water and sewerage systems often have coastal outlets, which may be covered by water during flooding, causing surcharging in the system and surface flooding far inland when water cannot drain through (Mosley, 1990). Many cities and towns around New Zealand are thus vulnerable.

NIWA has a computer model called EXTLEV that can calculate extreme sea levels based on tide data (NIWA, 1997). In theory this could be used to calculate return periods or exceedance probabilities for a given flood height. By adjusting the mean sea level by the climate change induced sea level rise the change in AEP could be calculated: eg. From Figure 7, a sea level rise of 3 m is exceeded with AEP of less than 0.0001, or about once every 14 years, but this rises to AEP 0.005, or about once every 3 months, with a 0.5 m sea level rise. What was once a rare event becomes very common.

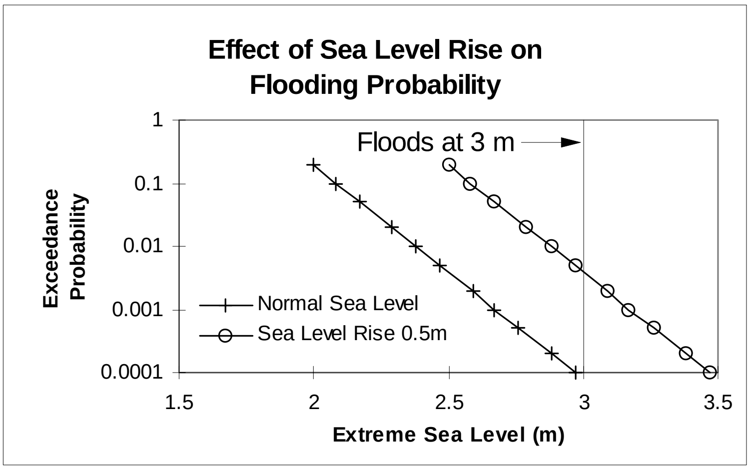

Figure 7. Change in exceedance probabilities with sea level rise (sample data only).

In practice, the EXTLEV model does not give realistic figures as wave surges are not modelled: in one case study for the Thames region a 1 in 500-year event as modelled by EXTLEV was observed historically every 20 years (Dahm, 1998). The EXTLEV model has not been used for analysis for this reason.

Coastal flooding is monitored by many local body organisations. For example, Environment Waikato is responsible for the Waikato and Thames/Coromandel region. Part of their job is to provide information to assess hazard lines. In the Thames district the hazard line is taken as 3 m above mean sea level, which gives an historical 1% AEP for flooding. This is above the 2% AEP hazard line required by the Acceptable Solution to NZBC Clause E1: “Surface Water”, which is at approximately 2.8 m, and so gives some buffer against future sea level rise. In one recent subdivision near Thames homes were built below the recommended level, and have been flooded several times. Expensive work on upgrading storm defences is underway. Environment Waikato are in the process of revising hazard lines to take into account possible future sea level rises, a process that will take three to five years, as more information is needed about waves in the Firth of Thames. They are not revising the stop-bank levels as they can be raised in the future if rises in sea level occur, avoiding the risk of incurring large unnecessary costs. (Dahm, 1998)

A recent initiative, the Coastal Hazards and Management Program (CHAMP) run by the International Global Change Institute at Waikato University, is being developed to analyse flooding risk and damage to coastal properties associated with sea level rise and climate change. This programme is not at a stage to provide useful information on building flooding risk and damage yet. FRST funding finished for this programme in 1998, though with widespread international interest it may continue.

A model relating flood height and speed to building damage exists for Australia (ANUFLOOD). The author is not aware of any similar models for New Zealand. Adapting this model to New Zealand would be a significant step forward in assessing the change in flooding risk.

If the likely sea level rise with climate change is a large fraction of the height of a coastal flooding event (for example on a sheltered coast), then the incidence of coastal flooding could increase dramatically. Houses on an estuary could face even more risk with the interaction of sea level rise and inland river flooding. If the combination of storm surges and high tides constitute most of the flood height, then a rise in sea level would have relatively less effect on the incidence of coastal flooding. A study of an Australian cyclone prone coastal area showed that the risk of flooding increased by about two times for a 60 cm sea level rise (Stark, 1987). The risk of flooding in sheltered areas would be expected to increase by much more than this. Thus the increase in the coastal flooding risk appears to be similar to the change in risk with inland flooding.

A sea level rise of 15 to 95 cm could cause foreshores to retreat by 20 to 80 m in sandy areas. This retreat would not generally be gradually, but in response to infrequent severe storms (Hicks 1990).

If tropical cyclones increase then there would be large increases in rainfall, storm surge, wind and wave-height. All of these factors increase the height and extent of coastal flooding, and may well be far greater than the sea level rise. In such a situation, low-lying houses near the coast would be at extreme risk.

At present the best assessment of changes in coastal flooding risk is to raise the 2% hazard line by the sea level rise and find the number of houses exposed to increased or new risk. This is of course extremely site specific, as tidal conditions and wave exposure are peculiar to a site, so a nationwide assessment of the increased risk is beyond the scope of this report.

14. DEGRADATION OF POLYMERS

The degradation of polymers is affected by many environmental and physical factors including: temperature; radiation (visible and UV); water and moisture; chemical agents (including salt); and thermal stress.

UV levels are currently increasing as ozone depletion is worsening, and are expected to peak early next century before recovering. By 2030 UV levels are expected to decrease from current levels by about 6-7%, and recover to 1975 levels by 2070 (see Section 18.10). These scenarios rely on current scientific understanding, and on the agreed reductions of CFCs and other ozone depleting compounds.

On the time scales considered for this report, UV levels should decrease. In the interim, levels will increase, resulting in increased degradation rates. As indicated in Section 3.9 the current state of scientific knowledge of UV polymer degradation is insufficient to quantify the effect of changes in UV radiation (Andrady et al, 1995). The chemical process by which polymers (including plastics and wood) degrade with UV are either unknown or poorly understood. Of those few that are understood the actual UV spectrum is extremely important, and changes in the relative amounts of UVA, UVB, and UVC radiation may have unexpected consequences.

Two important factors that affect the rate of degradation of polymers are the UV radiation and the surface temperature of the polymer itself. UV radiation breaks chemical bonds, and then subsequent reactions proceed at a rate determined by the temperature. This can lead to a complex behaviour with temperature. Generically, degradation rates have a threshold below which degradation is unaffected by temperature, and above which there is an exponential response (rate $\propto e^{T/14.4}$), such that the reaction rate approximately doubles every 10°C (Trebilco, 1997). The threshold is different for every polymer. By estimating the change in surface temperature with climate change, an estimate of the generic change in degradation rate can be attempted.

The surface temperature of a surface is influenced by numerous factors including the properties of the material, air temperature, solar radiation and wind speed. Some modelling work on surface temperatures in New Zealand has been done by Trethowen and Eyles (1990), using the formula:

$$T_s = T_a + [R_s(\alpha.I - f.E.I_l)] \qquad (1)$$

where

T_s = surface temperature in °C

T_a = air temperature in °C

I = solar radiation intensity

α = absorption coefficient (black=0.8, white=0.4)

R_s = external surface resistance

E = longwave emittance of surface

I_l = longwave radiation from a black surface

f = sky view factor (horizontal = 1, vertical = 0.5)

The external surface resistance, R_s is a measure of heat loss to surroundings, and given by:

$$R_s = 1/(11+1.5*V)\,\mathrm{m}^2.{}^\circ\mathrm{C/W} \qquad (2)$$

where V is the windspeed in knots.

Clearly, with the lack of reliable information on changes in most of these factors with climate change, it is not feasible to create scenarios of the temperature regime of building polymers at this stage. However, based on Equation 1, an increase in mean ambient temperature alone would be expected to result in the same increase in the surface temperature.

A rough estimate of the scale of increases in degradation rates for generic materials if temperatures rise uniformly by a constant amount can be determined by the following approach. If the reaction rate is exponential then:

$$\text{reaction rate} = ke^{T/\tau} \qquad (3)$$

where k is an arbitrary scaling constant, T is the temperature, and τ the reaction rate constant. If the distribution of polymer surface temperatures is $P(T)$, then the reaction damage D_T is:

$$D_T = \int_{T_{\min}}^{T_{\max}} ke^{T/\tau} P(T)\,dT \qquad (4)$$

If the polymer surface temperatures increase by a constant ΔT, then the new reaction damage $D_{T+\Delta T}$ is:

$$\begin{aligned} D_{T+DT} &= \int_{T_{\min}+\Delta T}^{T_{\max}+\Delta T} ke^{T/\tau} P(T-\Delta T)\,dT \\ &= \int_{T_{\min}}^{T_{\max}} ke^{(T+\Delta T)/\tau} P(T)\,dT \qquad (5) \\ &= e^{\Delta T/\tau} D_T \end{aligned}$$

which is simply a constant multiple of the original reaction damage D_T. If the reaction rate doubles approximately with each 10°C increase in temperature then τ=14.4, and the increase in reaction rates with increases in temperature with climate change are as given in Table 37, page 78.

Table 37. Estimate of maximum increase in reaction rates with increasing temperatures. (These figures are only valid if UV exposure remains constant).

	Temperature Increase	Reaction Rate Increase
2030, Low	0.28°C	2%
2030, High	0.92°C	7%
2070, Low	0.59°C	4%
2070, High	2.67°C	20%

Large increases in degradation rates could occur if the chemical process changes with a threshold in temperature or UV, or if the spectrum of UV light changes. For example in PVC, degradation accelerates for temperatures above about 50°C, as yellowing occurs which increases the absorption of radiation, increasing the temperature of the PVC further. Clear PVC sheeting becomes brittle and opaque, and may crack.

Extremely high surface temperatures are rare, and follow approximately an exponential distribution. For example, at present in Auckland a black, flat surface would only exceed 50°C about 800 hours per year (Trethowen and Eyles, 1990), but a 1°C increase in mean temperature would increase this to over 900 hours per year, a 13% increase. Modest temperature increases may increase the incidence of catastrophic failure if polymers have temperature thresholds, e.g. PVC.

In summary, if a polymer has no catastrophic change in the degradation reaction above a threshold temperature, then with climate change the rates will increase by at most the values indicated in Table 37, page 78, and are likely to be lower. Long-term decreases in UV may offset most of this increase, and may even result in a net decrease in degradation. The incidence of catastrophic failure due to extreme temperatures will increase for susceptible materials, e.g. PVC.

Other climate variables (eg. moisture, wind, salt) can have a major impact on the degradation of some materials, especially corrosion of metals. For example, increased rainfall or humidity could increase the time-of-wetness, increasing corrosion rates. Increased temperatures would have the opposite effect on time-of-wetness, but could increase the corrosion reaction rate. Increased wind speeds could increase salt levels, increasing corrosion rates. It was not presently feasible to model the effects of changes in climate variables other than UV and temperature, as their interactions (especially for corrosion) are complex.

15. STORM AND WIND DAMAGE

As discussed in section 18.7, page 93, and section 18.8, page 94, there is no consensus on possible changes in wind speed and direction, nor on changes in the incidence and severity of tropical cyclones. There is not even consensus on whether they will increase, decrease, or stay the same. However, if there is a possibility of increased incidence of extreme winds the effects cannot be ignored, as the potential extent for damage is large if changes occur. This is particularly true if there are changes in the occurrence of tropical cyclones.

Design wind speeds for structural design are derived using two methods: NZS 3604:1999 or NZS 4203 (1992). They are based on the unmodified wind speed that has an historical 5% chance of exceedance in 50 years. These windspeeds are fairly uniform across the seven New Zealand wind zones, only varying from 42-49 m/s (151-176 km/hr), though the wind pressure on buildings varies by about 60% across these basic design wind speeds.

Building exposure is the major factor in structural design, and is used to modify these basic design wind speeds, giving a range of more than three times in the actual design wind speed from completely sheltered to completely exposed buildings within a region. A structure is expected to fail once the design limits are exceeded. Failure could be anything from partial loss of the roof, to complete collapse of the building.

NZS 3604:1999 provides a simplified method for light timber framed buildings. It divides the country into two wind zones, and into five topographic exposure classes. From these factors the design wind speed is categorised as:

Code	*Description*	*Wind Speed (m/s)*
L	Low	32
M	Medium	37
H	High wind	44
VH	Very High	50
SD	Specific Design using NZS 4203 (1992)	NA

The structural requirements based on this method are conservative, and not specific to any one wind direction, so the risk of wind damage to timber framed house designs based on NZS 3604:1999 should not exceed that prescribed by the NZBC for slight increases in maximal wind speed. Houses assessed at the margin of a wind speed category may be more vulnerable to increases in wind speed.

NZS 4203 (1992) provides a more comprehensive method, and is used to make a more precise estimate of the design wind speed. It is based on more wind zones, and calculates the exposure from factors representing site height, terrain, shielding, and topography, in conjunction with the wind direction. Design speeds will generally be less conservative than those calculated according to NZS 3604:1999 (which are derived from NZS 4203 (1992)).

Earthquake loadings are also specified in these two standards. For some homes the structural requirements for earthquakes will exceed the wind requirements, so these houses will not be vulnerable to increases in wind speed until the wind loading exceeds the earthquake loading. This may be the case for some sheltered homes in the ‘A’ high earthquake loading zones (lower North Island and upper South Island).

It is interesting to note that the wind risks are at the 0.1% annual exceedance probability, while flooding risks at a 2% annual exceedance probability are 20 times more conservative.

Houses that are most vulnerable are those that are already at the limits of their structural design, which could be any house in any exposure class. Houses that have been constructed to a lower standard than the current NZBC, or have structural defects, or are suffering deterioration of fasteners or structural elements would be the most vulnerable.

It would appear that the design wind speeds are conservative, so for many houses the possible increases in wind speed with climate change (excluding tropical cyclones) are unlikely to increase the risk of wind damage beyond that prescribed by the NZBC. In any case, as the occurrence of damaging winds is extremely low, and the climatology of wind not well defined, it would be very difficult to determine if there is a change in the risk of extreme winds as a result of climate change in a 50-year time span (see section 6.3, page 40).

Wind damage to buildings can include damage to windows or guttering from direct wind, flying debris or fallen trees. Levels of such wind damage would be expected to increase with increasing wind speeds as the impact energy would be higher.

By definition, the threshold wind speed for a hurricane is >32 m/s (155.2 km/hr) windspeed, however the eye of hurricanes can have winds over 250 km/hr, with mean speeds in a 75 km radius above 175 km/hr (Briggs and Smithson, 1985). The Australian building loading code contains design wind loadings for cyclone prone areas (AS 1170.2, 1989). The basic design speed for ultimate load in cyclone prone areas is 60-85 m/s (216-306 km/hr), depending on the region’s exposure to cyclones.

The basic design wind speed for Northland is 176.4 km/hr (NZS 4203, 1992), so a full-strength tropical cyclone with the eye tracking near Northland would be expected to destroy many buildings in its path. A substantial increase in the design wind loadings would be needed if tropical cyclones start to arrive at strength in New Zealand in significant numbers, and wide-spread damage to existing buildings would be expected from wind alone.

The structural strength of a home can often be increased easily and cheaply, for example by adding more nails to the galvanised steel roofing, adding additional bracing, or strengthening the connection between the roof and walls. These may add only a few hundred dollars to the initial cost of a home. Many strengthening measures may also be done at low cost after the house is completed, provided there is access to the roof-space.

16. TROPICAL CYCLONES

The frequency and severity of tropical cyclones has increased this century: Fiji was hit by 12 between 1940 and 1979, while 10 occurred between 1981 and 1989 (Nunn, 1990). The worlds largest reinsurance company stated in a special report that:

> "… if water temperatures increase by 0.5 to 1.0 degree C in the course of the next few decades we can expect an extension of the hurricane season by several weeks and a considerable increase in the frequency and intensity of hurricanes. … This applies above all to tropical cyclones, which will penetrate moderate latitudes and thus affect areas so far not exposed to risk" (Munich Re, 1990).

Whether the incidence or intensity of tropical cyclones over New Zealand changes with climate change is uncertain at present (see section 18.8, page 94). What is certain is that if tropical cyclones do increase then there will be major damage to many homes in the north of New Zealand. Some of these potential impacts are discussed in previous sections on wind and flooding. The severity of damage may vary depending on whether the cyclone tracks down the west or east side of the North Island. Cyclones tracking down the west side tend to have stronger winds on land, as the velocity of the cyclone is added to the velocity of the northerly winds on the eastern side of the cyclone. The reverse occurs for cyclones tracking down the east side of the North Island, however the initial wind, storm surge and waves would drive into the more populated east coast. Only once the cyclone eye is well down the North Island do the winds come from a westerly direction and drive into the west coast, and by then a cyclone would be expected to have lost some strength.

A study by Reid (1989) concluded that with climate change, tropical cyclones may become the dominant cause of high wind speeds for design purposes in the Auckland region, and probably much of the North Island, and that an increase in design wind speed of at most 10% should be adequate for the scenarios considered.

In summary, the likelihood of changes in the frequency, scale, or path of tropical cyclones is unknown, but the potential impacts are major.

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18. NIWA REPORT TO BRANZ: CLIMATE CHANGE SCENARIOS FOR THE CONSTRUCTION INDUSTRY

A.B. Mullan, 19 May 1998

This brief and informal report is part of NIWA's contribution to FRST Contract BRA605, Objective 1, on "Implications of Climate Change for the Construction Industry". It provides the scientific background to the scenarios provided to BRANZ, and is based on the latest IPCC findings and previous research in New Zealand.

18.1 Scenario Construction

There are many uncertainties in projecting how local climate might change. A basic difficulty is that there are multiple causes of climate variability and change, that operate over a range of timescales from interannual (random or chaotic dynamics, El Nino events, volcanic eruptions) to multidecadal (trends in ocean temperatures and cryosphere, and trends in atmospheric composition). As far as the anthropogenic (man-made) component is concerned, future emissions of climatically active pollutants, such as the sulphate aerosols and the many greenhouse gases, depends on political decisions which cannot be easily predicted.

Even in the simplest case of a prescribed greenhouse gas increase, which until recently was the primary emphasis of global climate change modelling, the situation is far from simple. General circulation models (GCMs) vary considerably in their sensitivity to the same imposed greenhouse gas increase, and observations cannot tell us the 'correct' value with any precision. When projections are 'downscaled' to produce local climate changes, there are further difficulties. While most state-of-the art GCMs agree in the *pattern* of change at the global scale (if not the magnitude), they tend to disagree at the smaller scale that would encompass the Tasman Sea-New Zealand region. Nevertheless, assessments of regional climate change need to be made to allow the estimation of impacts on the economy, or specifically for this report, on the construction industry.

Because of these uncertainties, regional climate changes are estimated through the development of *scenarios.* A scenario is a description of a plausible future climate that is consistent with the results of relevant GCM simulations. Scenarios need to take into account both the broad range of scenarios for greenhouse-gas emissions (and ideally sulphate aerosol changes too), the range of climate sensitivities suggested by GCMs, and the range of local circulation responses. Scenarios involve many simplifying assumptions, and future changes outside the range of the scenario cannot be excluded. Scenarios should not be viewed as predictions, and to minimise this confusion it is always best to deal with a range of scenarios rather than a single one.

The scenarios we present here are based on those developed for Australia and New Zealand by Whetton *et al.* (1996). There is a two-step process involved. First, we make use of curves of global temperature increase and global sea level rise produced by the latest IPCC report (Houghton *et al*., 1996). The global changes are then converted to New Zealand changes on the basis of results from a number of GCMs.

18.2 Global Warming and Sea Level Rise Scenarios

We focus on developing scenarios at two particular points in time, the years 2030 and 2070. The projected global mean temperature up to 2100 is given in Fig 19 of IPCC (1996) which summarises the findings of the Second Scientific Assessment of the Intergovernmental Panel on Climate Change. This figure shows a number of curves that diverge over time. The lower limit is associated with a low climate sensitivity (of 1.5°C) combined with the IS92c[x] low emission scenario, and the upper limit with a high climate sensitivity (of 4.5°C) along with the IS92e high emission scenario. Consequences of sulphate aerosol changes are also taken into account. Similarly the projected global mean sea level rise extremes are taken from figure 21 of IPCC (1996), that covers the range from low climate sensitivity/IS92c emission scenario/low ice melt parameters to high climate sensitivity/IS92e emission scenario/high ice melt parameters.

Global temperatures range from 0.35-1.25°C warmer by 2030, with a mid-range value of about 0.6°C, to 0.75-3.05°C warmer by 2070 (mid-range 1.5°C). The corresponding mid-range values for sea level rise are 12 cm in 2030 and 32 cm in 2070. These changes are slightly smaller than those derived by Whetton *et al*. (1996). The regional scenarios described below are based on these scenarios of global warming.

Table 38. Projected global mean surface temperature change extremes (in degrees C) and sea level rise extremes (in cm).

	Global Temperature (°C)		**Sea Level Rise (cm)**	
Year	**Low Extreme**	**High Extreme**	**Low Extreme**	**High Extreme**
2030	0.35	1.25	4	24
2070	0.75	3.05	10	60

18.3 New Zealand Mean Temperature and Rainfall Scenarios

There are a range of techniques that can be used to relate local climate to larger scale climate and circulation patterns (Giorgi and Mearns, 1991). Collectively, we can refer to these techniques as *downscaling*. The approach used here is based on deriving statistical relationships between observed variations in temperature and rainfall at New Zealand sites and larger scale variations in temperature, precipitation and circulation fields. These relationships are then applied to the simulated GCM changes. The method is described in Mullan (1994) and Whetton *et al.* (1996), and has been used by Mullan and Renwick (1990), and by Mullan and Salinger (1994) in the FRST-funded CLIMPACTS programme.

The use of observed data to specify the station-to-large scale relationships does impose a geographic pattern on the results (e.g., Figure 8, page 107) which may not necessarily hold in a future climate. The only feasible alternative at this time is to downscale by nesting a finer mesh regional model within the GCM. This has been done for New Zealand (Salinger and Mullan, 1997; Renwick *et al*., 1998) for a single GCM – that developed by the CSIRO, and one of the five models used in the statistical downscaling. See also Basher and Pittock (1998), for a useful discussion of climate scenarios appropriate to Australia and New Zealand.

It should be noted that these scenarios use results where a global atmosphere is coupled to a ‘slab-ocean’ that is a moisture source, and has heat capacity but no currents. With such a simplified lower boundary, the atmosphere model simulations have to be treated in an ‘equilibrium’ sense, so climate change experiments focus on current climate and a doubled-CO_2 climate. With a more realistic 3-dimensional treatment of a dynamical ocean that is now possible in the latest models, climate change experiments can examine ‘transient’ changes where incremental CO_2 concentration changes occur year by year. These transient simulations suggest climate warming will occur much more slowly in the Southern Hemisphere than projected by the equilibrium models. In fact, far from the South Pole warming faster than the

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[x] The IS92 series of scenarios are a number of climate change scenarios developed by the IPCC and widely used in climate change research.

equator, with consequent weakening of the mid-latitude westerly winds, the transient ocean-atmosphere GCMs indicate an initial strengthening of the pole to equator temperature gradient in the Southern Hemisphere and a strengthening of the westerlies. This underscores the danger of taking scenarios too literally as predictions, when at this stage of climate change science, they should only be used in a sensitivity exercise.

Figure 8, page 107, shows the *sensitivities* of New Zealand temperature and precipitation changes to a 1°C increase in global average surface temperature. At each New Zealand site, the simulated changes from five equilibrium GCMs are scaled to unit global temperature increase, then ranked from 1 (highest) to 5 (lowest). The High and Low cases are the rank 2 and 4 results respectively; that is, following Whetton *et al*. (1996), we have deliberately excluded the highest and lowest of the GCM simulations at each station point as 'outliers'.

We must then multiply this local sensitivity per degree global change by the range of global temperature projections at 2030 and 2070. Scenario changes were calculated for each month. The changes in the monthly mean temperature are then used in various BRANZ analyses, and in further development of the extreme temperature scenarios below. Table 39, page 91 summarises the annual mean temperature and precipitation changes for four sites: Auckland (Whenuapai), Wellington (Kelburn), Christchurch and Invercargill.

Table 39. Scenarios of annual average change in temperature (in degrees C) and in precipitation (in %), for 'low' and 'high' scenarios at 2030 and 2070. Note that the 2 decimal point precision is not warranted, but is used in modelling for consistency.

Temperature	2030 Low	2030 High	2070 Low	2070 High
Auckland	0.27	0.88	0.57	2.55
Wellington	0.28	0.94	0.60	2.73
Christchurch	0.29	0.97	0.62	2.81
Invercargill	0.27	0.90	0.58	2.61

Precipitation	2030 Low	2030 High	2070 Low	2070 High
Auckland	0.8	7.5	1.5	21.7
Wellington	-4.7	-0.3	-13.5	-0.5
Christchurch	-3.0	0.4	-8.8	1.3
Invercargill	-0.6	4.0	-2.0	11.7

18.4 Extreme Temperatures

The occurrence of extreme daily temperatures has also been identified as an important climate change factor for the building industry. A simple statistical model is used here to simulate daily temperature variations about a smooth annual cycle. The model, known technically as a first-order autoregressive model (or 1st-order Markov model), has been widely used in climate change assessments (Mearns *et al*., 1984; Salinger *et al*., 1990). Daily temperature departures are modelled in terms of a one-day lag autocorrelation and a random or 'noise' component. The autocorrelation recognises that unseasonally warm days (or unseasonally cold ones) tend to group together, rather than being randomly spaced through the record.

The approach used is that for each site, we take the daily maximum temperature record for the 1961-1990 period, and compute the two model parameters (autocorrelation and noise standard deviation) for the present climate. For a changed climate, we perturb the seasonal cycle according to the various high/low scenarios described in the previous section, and rerun the daily simulations to generate a new sequence of daily temperatures. We can identify important high temperature thresholds, such as 25°C and 30°C, and simply count the number of days exceeding these values.

Two sets of assumptions are involved in this model. Firstly, the monthly increments to the 1961-1990 temperatures are applied to the maximum temperature data, when the scenarios were developed for the mean temperature changes, where 'mean' here is the average of maximum and minimum values. It was necessary to do this because GCM data for maximum temperatures was not available for this study. However, it is believed that maximum temperatures may not increase quite as fast as minimum temperatures under global warming. Many observational studies have reported a decrease in the diurnal temperature range over the past 30 years (e.g., see Salinger *et al*., 1996, for New Zealand). Also, GCMs indicate a reduction in the diurnal temperature range over land in most places and seasons (IPCC, 1996). A GCM simulation described in the Second IPCC Assessment (Kattenberg *et al.,* 1996) indicates a decrease of 0.3°C in diurnal range for a mean temperature increase of 1.6°C. This result would scale to maximum temperature increasing at approximately 90% of the rate of the mean temperature (and minimum temperature increasing at 110%). This is slightly more conservative than recent observations (Karl *et al*., 1993) that indicate worldwide increases in minimum land-surface air temperature since 1950 of about twice those in maximum temperature (implying maximum temperature increases at 66% of the rate for the mean).

The second assumption in the model is that the variability parameters (autocorrelation and standard deviation) are kept constant in a changed climate. Some authors have highlighted that variability changes could be very important (e.g., Katz and Brown, 1992); however, whereas GCMs all agree on an increase in mean temperatures, there is not much agreement on how day to day variability could change (Kattenberg *et al*, 1996). Some models suggest a decrease in temperature variability, although these are confined primarily to high latitude regions where snow or sea-ice cover is reduced under global warming.

Table 40 indicates how well the Markov model validates on the current climate. The variation between sites in occurrence of days above 25°C is picked up well by the model, but there is a substantial underestimate of days above 30°C. This could possibly be improved by selecting a specific extreme value model, rather than a model that seeks to simulate temperature variation over its entire range; however, since days above 30°C hardly ever occur at the sites tested, it would be difficult to 'tune' a model to simulate them adequately. We expect then that this model will underestimate the frequency of the very highest extremes.

Table 40. Number of days per year above 25°C (D25) and 30°C (D30), at several New Zealand sites, for the present climate, as observed for the 1961-1990 period, and as simulated by a first order Markov model.

Site	**Observed**		**Simulated**	
	>25°C	**>30°C**	**>25°C**	**>30°C**
Auckland	21.6	0.0	20.3	0.0
Wellington	3.8	0.1	3.1	0.0
Christchurch	31.5	5.5	25.9	2.1
Invercargill	5.6	0.0	1.6	0.0

Table 41 shows the change in occurrence of days above 25°C and 30°C for the four scenarios of Table 39, page 91. Note the much more rapid increase in days above 25°C in Auckland compared to Christchurch. This occurs because the day to day variability is smaller for Auckland, and even in the current climate the maximum temperature often exceeds 25°C over the summer.

Table 41. Change in number of days above 25°C and 30°C, between the present (1961-90 conditions) and 2030 and 2070 for the low and high sensitivity scenarios.

Site	**2030 Low >25°C**	**2030 Low >30°C**	**2030 High >25°C**	**2030 High >30°C**	**2070 Low >25°C**	**2070 Low >30°C**	**2070 High >25°C**	**2070 High >30°C**
Auckland	4.5	0.1	16.7	0.2	10.3	0.1	60.5	1.6
Wellington	0.8	0.0	3.5	0.0	2.0	0.0	18.2	0.3
Christchurch	3.0	0.4	10.1	1.5	6.3	0.9	37.7	7.3
Invercargill	0.4	0.0	1.7	0.0	1.0	0.0	8.9	0.1

18.5 Extreme Rainfall

Systematic increases in the intensity of daily rainfall are a common feature of many model simulations. These changes correspond to an increase in the frequency of heavy rainfall events, or alternatively, a reduction in the return period of these extremes. Such changes in the rainfall distribution, without necessarily implying an increase in the mean rainfall, are associated with stronger convective activity that is possible at higher temperatures. Scenarios for changes in the average return periods of heavy-rainfall events over Australia and New Zealand, as calculated by Whetton *et al*. (1996, see their figure 8), were as follows:

2030: No change through to a halving of the return period of heavy rainfall events.

2070: No change through to a fourfold reduction in the return period of heavy rainfall events.

18.6 Flooding

The impact of climate change on flooding needs to be considered in two parts: inland flooding, where heavy rainfall events and hydrological factors are important, and coastal flooding, where sea level rise is a major additional factor. Inland flooding was considered by Minnery and Smith (1996), but they were unable to come to any firm conclusion other than the statement that the return period of the 1-in-100-year flood was likely to decrease substantially in a warmer climate, as a consequence of increased heavy rainfall events.

A widely used resource in New Zealand for assessing inland flooding is the manual of McKerchar and Pearson (1989). This work, which does not deal with climate change, provides contoured maps over New Zealand that enables one to compute floods of various return periods anywhere in New Zealand for the ‘current’ climate. In order to compute the 100-year flood, for example, there are two quantities that are read off the maps and multiplied together (see figures 3.4, 3.5, 4.8, and 4.9 in McKerchar and Pearson, 1989). The first factor is the mean annual flood, normalised by catchment area: this quantity has a geographic distribution that closely follows the pattern of mean annual rainfall over the country. The implication is that changes in *annual* flooding probably relate quite well to changes in precipitation under a climate change scenario. The second factor, which multiplies the mean annual flood to give the 100-year flood, incorporates hydrological factors that are associated with rainfall variability at the specific location. This second factor is small on the west coast of the South Island (which is wet almost all the time so a 100-year flood is not much worse than a 1-year flood) but is large in eastern areas of the country where rainfall variability is greater. At this time, the most that we can say from GCM simulations is that the change in rainfall distribution described above is likely to increase rainfall variability, and this could aggravate flooding problems even in areas of mean rainfall decreases. Further work will be required to quantify the effects.

18.7 Wind Speed and Direction

Over New Zealand the prevailing wind direction is from the west-southwest. There are fluctuations seasonally, and even more so from year to year with such features as the El Nino-Southern Oscillation (ENSO) phenomenon. The prevailing winds will remain from the west under any likely climate changes in the next century, but there is some disagreement about whether these winds will strengthen (the transient model result) or weaken (equilibrium models).

Of more relevance to the construction industry is the occurrence of strong, damaging winds. Whether these will change in the future depends on how the climatology of mid-latitude and tropical storms alters. Current geographic wind features, such as relatively stronger winds through Cook Strait and in the lee of the Southern Alps will, of course, be unchanged in an altered climate.

For mid-latitude storms, the travelling depressions of latitudes 40-60S, the main energy source is the equator-to-pole temperature gradient. However, increases in water vapour in the atmosphere (that produces latent heating on condensation) can also be important, and there is little agreement between models on expected changes in storminess in a warmer world (Kattenberg *et al*., 1996).

18.8 Tropical Cyclones

Tropical cyclones affect New Zealand only rarely, but when they do the consequences can be dramatic. There is some association between decaying tropical cyclones tracking near northern New Zealand and the El Nino-Southern Oscillation phenomenon. During La Nina conditions tropical cyclones are more likely to affect New Zealand than during normal or El Nino phases (Basher and Zheng, 1995).

The formation and intensity of tropical cyclones depend on a number of factors in addition to sea surface temperature (SST), and the popular belief that the region of cyclogenesis will expand with the 26°C SST isotherm is a fallacy (Henderson-Sellers *et al*., 1998). Recent results are particularly conservative.

Royer *et al*. (1998) calculate seasonal tropical cyclone *frequency* from an empirical relationship comprising six key physical parameters, applied to GCM output for present and doubled CO_2 climates. They find a modest increase in tropical cyclone numbers in the Northern Hemisphere and a small reduction in the Southern Hemisphere, without any extension in the area of possible cyclone genesis. Most GCM studies have inadequate resolution to simulate tropical cyclones, but a recent high resolution study (Bengtsson *et al*., 1996) actually simulates a significant reduction in the number of tropical storms. Henderson-Sellers *et al*. (1998) also suggest little or no change in global frequency of tropical cyclones. In addition, Henderson-Sellers *et al*. (1998) conclude from their review of recent studies that the potential *intensity* of tropical cyclones is also likely to either remain the same or undergo a modest increase of up to 10-20%.

18.9 El Nino-Southern Oscillation (ENSO)

Temperature and precipitation patterns over New Zealand vary from year to year with the state of the El Nino-Southern Oscillation (Mullan,1995). Given the above association between the La Nina phase of ENSO and increased incidence of tropical cyclones near northern New Zealand, it is apparent that future New Zealand climate change is closely linked to what happens with the ENSO cycle.

The equilibrium atmospheric GCMs with ‘slab’ oceans are unable to simulate ENSO events, but more recent transient coupled ocean-atmosphere GCMS have generated ENSO-like features. At present, however, there is not much confidence in model projections, and the consensus view (Whetton *et al*., 1996) is the fairly noncommittal one that ENSO extremes will continue to occur and changes in frequency and intensity are possible.

The occurrence of more frequent El Ninos since 1980, and the very long-running 1991- 95 El Nino, has resulted in speculation that anthropogenic climate change is altering observed ENSO frequencies (Trenberth and Hoar, 1996). However, this assertion has also been disputed by other authors, such as Harrison and Larkin (1997), who maintain that the prolonged ENSO conditions of the early 1990s might be expected by chance.

18.10 Cloudiness, Sunshine Hours and Ultraviolet Radiation

There is very little information in the Second IPCC Assessment (Houghton et al., 1996) about possible changes to sunshine hours and ultraviolet radiation. Both factors depend on changes in cloudiness, which is a major area of disagreement between GCMs. Thus, the radiative effects of clouds and their linkages to the hydrological cycle remain a major uncertainty for climate modelling (Dickinson *et al*., 1996).

Even the sign of the cloud-climate feedback is unknown, and in current GCMs changes in cloudiness can either amplify global warming (positive feedback) or constrain it (negative feedback).

Thus, there appears little basis at present for putting forward a scenario of cloud changes. This is in spite of the fact that observed decreases in the diurnal temperature range have been linked to increases in total cloud amount (Karl *et al*., 1993).

There have been systematic decreases in total ozone at mid-latitudes in both hemispheres, averaging -4 to -5% per decade since 1979 (Schimel *et al*., 1996). These reductions have been attributed largely to an increase in halocarbons, although there was a large transient loss associated with the 1991 Mt Pinatubo eruption.

On the basis of these ozone changes alone, we would expect ultraviolet radiation to have increased over the last two decades. McKenzie *et al*. (1991) show that for Lauder, Central Otago, a 1% ozone reduction typically causes an increase in erythemally active UV of 1.25 +/- 0.20%. They also note that clouds can frequently attenuate clear sky irradiances by more than 50%, so clearly future cloud changes are of major importance.

Those extrapolations of long-term surface UV irradiance changes that are available depend on assumptions of stratospheric ozone changes, and make no allowance for cloudiness trends. According to the latest assessment (IPCC, 1996; Prather *et al*., 1996; Slaper *et al*.,1996), recovery of stratospheric ozone should begin around the turn of the century, and should be complete shortly after 2050. This scenario depends on the much stricter 1992 Copenhagen Amendments to the 1987 Montreal Protocol for international restrictions on the production of ozone-depleting substances. Under this scenario, the Antarctic ozone hole would also continue to occur annually until about 2050.

Thus, in terms of our scenarios for 2030 and 2070, the simplest scenario is for UV levels to *decrease* from current levels by about 6-7% by 2030, and be about 10% lower than current levels in 2070 (ie, back to levels observed around 1975).

18.11 References to NIWA report

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Table 42. Monthly temperature changes for 2030, low end of range

Name	Lat	Long	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Auckland	36.8	174.8	0.27	0.27	0.27	0.27	0.27	0.28	0.28	0.27	0.26	0.26	0.26	0.26	0.27
Wellington	41.3	174.8	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Christchurch	43.5	172.6	0.28	0.28	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.3	0.29	0.29	0.29
Invercargill	46.4	168.3	0.25	0.26	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.26	0.27
Tauranga	37.7	176.2	0.27	0.27	0.27	0.27	0.27	0.28	0.28	0.28	0.27	0.27	0.27	0.27	0.27
Ruakura	37.8	175.3	0.27	0.28	0.27	0.27	0.28	0.28	0.29	0.28	0.27	0.26	0.26	0.27	0.27
Taumaranui	38.9	175.3	0.28	0.29	0.28	0.28	0.28	0.29	0.29	0.28	0.28	0.27	0.28	0.28	0.28
New Plymouth	39	174.2	0.27	0.28	0.28	0.28	0.28	0.29	0.28	0.28	0.27	0.27	0.27	0.27	0.28
Napier	39.5	176.9	0.24	0.23	0.23	0.22	0.22	0.23	0.23	0.23	0.23	0.23	0.24	0.24	0.23
Nelson	41.3	173.1	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Queenstown	45	168.7	0.3	0.31	0.32	0.32	0.32	0.32	0.32	0.33	0.33	0.32	0.32	0.3	0.32
Dunedin	45.9	170.5	0.25	0.26	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.26	0.27

Table 43. Monthly temperature changes for 2030, high end of range

Name	Lat	Long	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Auckland	36.8	174.8	0.88	0.88	0.88	0.87	0.86	0.86	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Wellington	41.3	174.8	0.93	0.92	0.94	0.94	0.97	0.96	0.96	0.94	0.93	0.92	0.91	0.92	0.94
Christchurch	43.5	172.6	0.93	0.94	0.96	0.98	1.03	1.02	1.02	0.98	0.96	0.94	0.92	0.92	0.97
Invercargill	46.4	168.3	0.89	0.89	0.88	0.9	0.92	0.94	0.93	0.9	0.89	0.88	0.88	0.88	0.90
Tauranga	37.7	176.2	0.89	0.9	0.9	0.88	0.88	0.88	0.9	0.89	0.88	0.89	0.89	0.9	0.89
Ruakura	37.8	175.3	0.9	0.91	0.91	0.9	0.89	0.89	0.9	0.89	0.89	0.9	0.91	0.91	0.90
Taumaranui	38.9	175.3	0.93	0.93	0.92	0.91	0.91	0.92	0.93	0.92	0.92	0.93	0.94	0.94	0.93
New Plymouth	39	174.2	0.91	0.92	0.91	0.9	0.9	0.9	0.91	0.92	0.91	0.91	0.91	0.92	0.91
Napier	39.5	176.9	0.76	0.77	0.77	0.75	0.76	0.76	0.77	0.76	0.74	0.74	0.74	0.75	0.76
Nelson	41.3	173.1	0.98	0.96	0.96	0.95	0.98	0.98	0.98	0.96	0.95	0.95	0.96	0.97	0.97
Queenstown	45	168.7	1.07	1.06	1.06	1.05	1.07	1.07	1.08	1.05	1.05	1.06	1.08	1.07	1.06
Dunedin	45.9	170.5	0.89	0.89	0.89	0.91	0.95	0.96	0.95	0.92	0.9	0.89	0.88	0.89	0.91

Table 44. Monthly temperature changes for 2070, low end of range

Name	Lat	Long	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Auckland	36.8	174.8	0.57	0.58	0.57	0.58	0.58	0.59	0.59	0.58	0.57	0.56	0.56	0.56	0.57
Wellington	41.3	174.8	0.6	0.61	0.61	0.6	0.59	0.59	0.59	0.6	0.6	0.6	0.6	0.6	0.60
Christchurch	43.5	172.6	0.61	0.61	0.62	0.62	0.62	0.62	0.62	0.63	0.63	0.64	0.63	0.62	0.62
Invercargill	46.4	168.3	0.53	0.55	0.58	0.6	0.6	0.59	0.59	0.59	0.59	0.59	0.58	0.55	0.58
Tauranga	37.7	176.2	0.58	0.58	0.58	0.58	0.59	0.6	0.61	0.59	0.57	0.57	0.57	0.58	0.58
Ruakura	37.8	175.3	0.59	0.59	0.58	0.58	0.59	0.61	0.61	0.6	0.58	0.56	0.56	0.58	0.59
Taumaranui	38.9	175.3	0.61	0.62	0.61	0.61	0.62	0.62	0.62	0.6	0.59	0.59	0.6	0.6	0.61
New Plymouth	39	174.2	0.58	0.6	0.59	0.6	0.6	0.61	0.61	0.59	0.57	0.57	0.57	0.58	0.59
Napier	39.5	176.9	0.52	0.5	0.48	0.48	0.48	0.5	0.5	0.5	0.49	0.5	0.51	0.52	0.50
Nelson	41.3	173.1	0.62	0.63	0.63	0.63	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Queenstown	45	168.7	0.65	0.67	0.68	0.69	0.68	0.68	0.69	0.69	0.7	0.7	0.68	0.66	0.68
Dunedin	45.9	170.5	0.55	0.56	0.59	0.61	0.61	0.61	0.6	0.6	0.6	0.6	0.58	0.56	0.59

Table 45. Monthly temperature changes for 2070, high end of range

Name	Lat	Long	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Auckland	36.8	174.8	2.55	2.57	2.55	2.52	2.5	2.51	2.55	2.55	2.55	2.56	2.56	2.57	2.55
Wellington	41.3	174.8	2.72	2.69	2.72	2.72	2.82	2.8	2.79	2.74	2.7	2.67	2.66	2.68	2.73
Christchurch	43.5	172.6	2.7	2.73	2.8	2.85	2.99	2.96	2.95	2.83	2.79	2.73	2.68	2.69	2.81
Invercargill	46.4	168.3	2.59	2.58	2.57	2.61	2.68	2.72	2.69	2.62	2.59	2.56	2.57	2.57	2.61
Tauranga	37.7	176.2	2.59	2.62	2.61	2.57	2.56	2.57	2.61	2.59	2.57	2.59	2.59	2.61	2.59
Ruakura	37.8	175.3	2.62	2.65	2.65	2.63	2.59	2.58	2.61	2.6	2.6	2.62	2.64	2.65	2.62
Taumaranui	38.9	175.3	2.72	2.72	2.69	2.65	2.65	2.68	2.71	2.69	2.68	2.71	2.73	2.74	2.70
New Plymouth	39	174.2	2.66	2.67	2.65	2.63	2.61	2.63	2.66	2.67	2.65	2.66	2.66	2.68	2.65
Napier	39.5	176.9	2.21	2.22	2.23	2.19	2.21	2.21	2.23	2.19	2.16	2.14	2.15	2.18	2.19
Nelson	41.3	173.1	2.84	2.78	2.79	2.77	2.84	2.84	2.83	2.79	2.77	2.77	2.8	2.81	2.80
Queenstown	45	168.7	3.11	3.08	3.09	3.06	3.11	3.12	3.13	3.05	3.05	3.07	3.13	3.11	3.09
Dunedin	45.9	170.5	2.59	2.59	2.6	2.65	2.76	2.78	2.77	2.68	2.63	2.58	2.56	2.58	2.65

Table 46. Monthly precipitation changes for 2030, low end of range

Name	Lat	Long	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Auckland	36.8	174.8	1.3	1.5	1.1	1.5	0.8	1.1	0.4	0.5	-0.4	-0.1	0.3	1.3	0.78
Wellington	41.3	174.8	-3.1	-2.7	-3.8	-4.4	-6.5	-5.7	-5.2	-4.6	-5.1	-5.9	-4.8	-4	-4.65
Christchurch	43.5	172.6	-2	-2.5	-3.3	-3.2	-4.5	-4.5	-4	-3.6	-3.3	-2.9	-1.4	-1	-3.02
Invercargill	46.4	168.3	0.5	-1.2	-1.8	-2.2	-0.6	0.3	0.6	0.7	0.5	-1.2	-1.3	-1.4	-0.59
Tauranga	37.7	176.2	2	2.6	1.9	2.6	1.7	2.1	1.4	1.4	1.1	1.1	1.5	2.1	1.79
Ruakura	37.8	175.3	2.3	2.3	1.8	2	1.6	1.9	1.4	1.3	1	1.7	2.1	2.6	1.83
Taumaranui	38.9	175.3	1.9	1.4	1.1	1	1	1.2	1	1	0.7	1.5	1.9	2.4	1.34
New Plymouth	39	174.2	1.4	1.1	1	1	0.9	1.1	0.7	0.7	0.5	1.1	1.4	1.6	1.04
Napier	39.5	176.9	0.9	0.9	-0.1	-0.4	-3.7	-4.2	-4.8	-2.5	-1.9	-1.2	-0.2	0.7	-1.38
Nelson	41.3	173.1	1.3	1.8	1.7	1.8	1.2	1.3	0.8	0.8	0.4	0.6	0.7	1.1	1.13
Queenstown	45	168.7	-0.2	-0.9	-1	-0.2	0.3	0.7	0.4	0.4	0	-2.1	-1.9	-1.7	-0.52
Dunedin	45.9	170.5	1.8	1.5	1.3	1.6	1.5	1.4	1.7	1.8	1.9	1.7	1.9	2.1	1.68

Table 47. Monthly precipitation changes for 2030, high end of range

Name	Lat	Long	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Auckland	36.8	174.8	9.4	9.4	9.7	9	6	5.7	4.6	5.9	4.4	6.8	8.6	10.1	7.47
Wellington	41.3	174.8	0.7	-0.3	-0.2	-0.3	-0.8	-1	-1	-0.8	-0.8	-0.7	0.5	0.7	-0.33
Christchurch	43.5	172.6	1.2	1.9	0.9	0.9	-0.4	-0.4	-0.2	0	0	-0.3	0	1.1	0.39
Invercargill	46.4	168.3	4.6	1.9	2.3	2.6	5	4.8	4.6	3.6	3.1	4.3	5.5	5.9	4.02
Tauranga	37.7	176.2	13.7	13.3	13.7	12.4	8.9	8.5	7.1	8.4	6.5	8.6	11.2	13.1	10.45
Ruakura	37.8	175.3	10.9	11.1	11	10.4	8	8.5	8	8.9	7.1	9.3	10.6	12.1	9.66
Taumaranui	38.9	175.3	9	8.3	8.1	7.9	7.4	7.5	7.2	7.8	6.3	8.5	9.2	10.7	8.16
New Plymouth	39	174.2	7.6	7	6.8	6	5	5.3	5.3	6.1	4.8	5.8	6.6	7.8	6.18
Napier	39.5	176.9	7.1	8.2	8.6	7.9	4.1	3.4	3.2	3.4	2.8	3.6	6.1	7.1	5.46
Nelson	41.3	173.1	8.9	8.3	8.8	8.1	6.8	6	5.2	5.5	4.8	5	6.7	7.7	6.82
Queenstown	45	168.7	7.8	4.6	3.7	3.5	7.1	7.3	6.6	5.6	4.7	6.1	6.6	8.3	5.99
Dunedin	45.9	170.5	8.7	7.9	7.2	7.1	6.6	7.2	7.5	8.7	8.6	8	8	8.3	7.82

Table 48. Monthly precipitation changes for 2070, low end of range

Name	Lat	Long	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Auckland	36.8	174.8	2.7	3.2	2.3	3.2	1.5	2.2	0.7	1.1	-1.2	-0.4	0.3	2.8	1.53
Wellington	41.3	174.8	-8.9	-7.9	-10.9	-12.8	-18.7	-16.6	-15.1	-13.3	-14.8	-17.1	-13.9	-11.7	-13.48
Christchurch	43.5	172.6	-5.9	-7.4	-9.5	-9.4	-13.2	-13.1	-11.7	-10.6	-9.7	-8.3	-4.1	-2.9	-8.82
Invercargill	46.4	168.3	1	-3.6	-5.5	-6.5	-1.9	0.5	1.3	1.4	1.1	-4	-4	-4.2	-2.03
Tauranga	37.7	176.2	4.3	5.5	4.1	5.6	3.6	4.4	2.9	3	2.3	2.5	3.2	4.5	3.83
Ruakura	37.8	175.3	5	5	3.9	4.2	3.5	4.1	3	2.9	2.2	3.6	4.4	5.7	3.96
Taumaranui	38.9	175.3	4.1	3.1	2.3	2.1	2.2	2.5	2.1	2.1	1.5	3.1	4.1	5	2.85
New Plymouth	39	174.2	3	2.4	2.2	2.1	2.1	2.3	1.6	1.6	1.1	2.4	3	3.5	2.28
Napier	39.5	176.9	1.8	1.8	-0.7	-1.4	-10.9	-12.4	-13.9	-7.3	-5.5	-3.5	-0.7	1.5	-4.27
Nelson	41.3	173.1	2.8	3.9	3.6	3.9	2.5	2.8	1.8	1.7	0.9	1.2	1.6	2.4	2.43
Queenstown	45	168.7	-1	-2.7	-3	-0.7	0.7	1.5	0.8	0.8	-0.2	-6.2	-5.8	-5.3	-1.76
Dunedin	45.9	170.5	3.8	3.3	2.8	3.4	3.2	3	3.6	3.8	4	3.6	4.1	4.5	3.59

Table 49. Monthly precipitation changes for 2070, high end of range

Name	Lat	Long	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Auckland	36.8	174.8	27.4	27.3	28.1	26.1	17.4	16.6	13.5	17.1	12.9	19.8	25.1	29.4	21.73
Wellington	41.3	174.8	2.3	-0.6	-0.5	-0.8	-1.7	-2.1	-2.1	-1.7	-1.8	-1.6	1.8	2.3	-0.54
Christchurch	43.5	172.6	3.6	5.5	2.6	2.6	-0.9	-1	-0.4	0.2	0.1	-0.7	0.3	3.4	1.28
Invercargill	46.4	168.3	13.2	5.6	6.7	7.6	14.6	13.8	13.4	10.6	9	12.5	16	17.2	11.68
Tauranga	37.7	176.2	39.9	38.5	39.8	36.1	25.9	24.8	20.5	24.5	18.9	24.9	32.5	38	30.36
Ruakura	37.8	175.3	31.7	32.4	32.1	30.4	23.2	24.6	23.2	25.8	20.5	27	30.9	35.1	28.08
Taumaranui	38.9	175.3	26.1	24	23.5	22.9	21.4	21.7	20.9	22.6	18.4	24.7	26.7	31.1	23.67
New Plymouth	39	174.2	22.1	20.2	19.8	17.3	14.6	15.3	15.4	17.7	13.9	16.9	19.1	22.6	17.91
Napier	39.5	176.9	20.7	23.8	24.9	23	12.3	10.1	9.6	10	8.1	10.6	17.9	20.7	15.98
Nelson	41.3	173.1	26	24.3	25.5	23.7	19.7	17.4	15.1	16	14	14.5	19.4	22.4	19.83
Queenstown	45	168.7	22.8	13.4	10.7	10.2	20.7	21.1	19.2	16.3	13.7	17.7	19.3	24.3	17.45
Dunedin	45.9	170.5	25.2	23	21	20.8	19.3	20.9	21.8	25.4	24.9	23.2	23.3	24.2	22.75

18.12 Figures:

Figure 8: Annual change in New Zealand temperature (in degrees C) and precipitation (in %) per 1°C increase in global average surface temperature. Results are shown for so-called low response and high response cases. Contour intervals are 0.1°C for temperature, and 2.5% for precipitation.

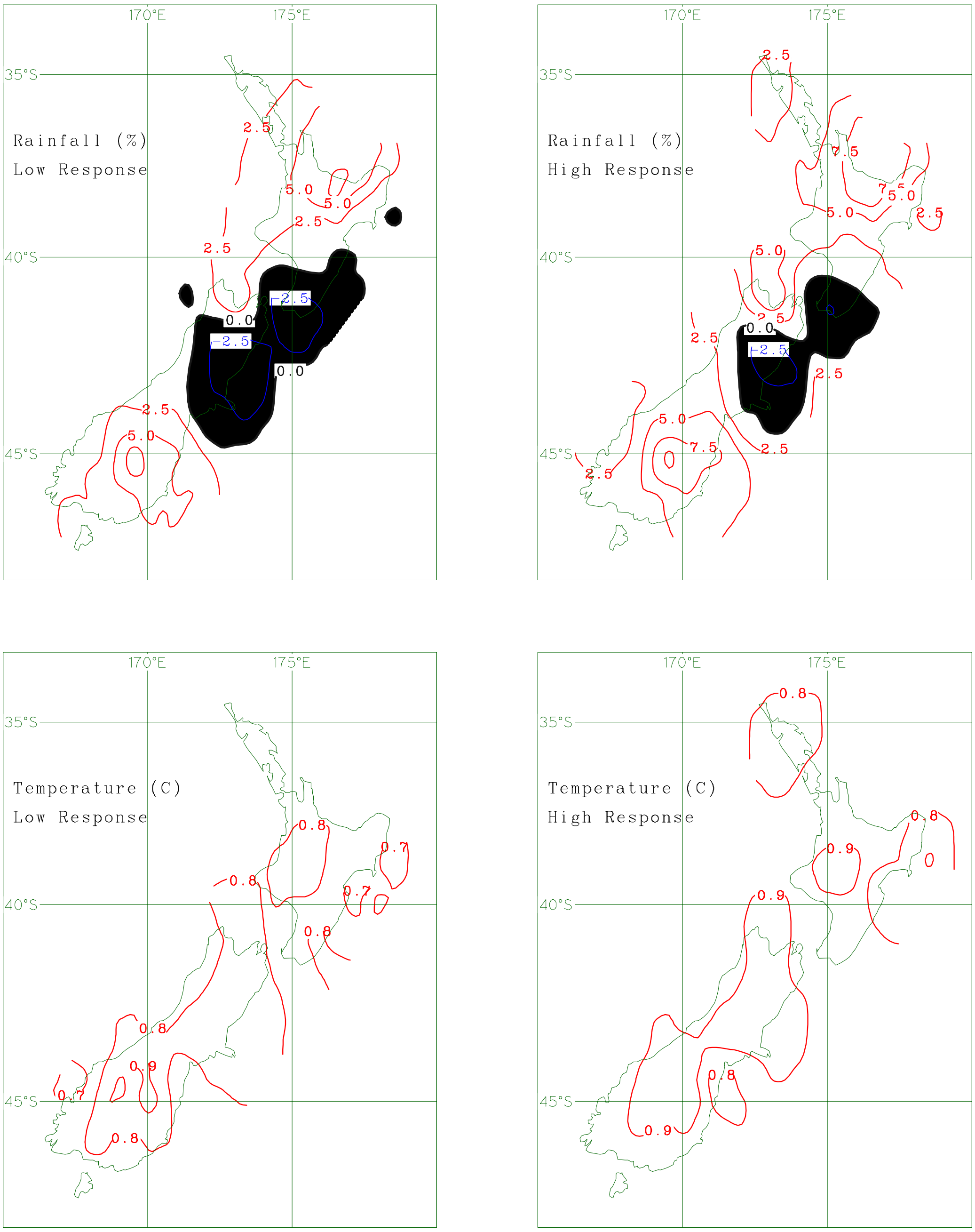
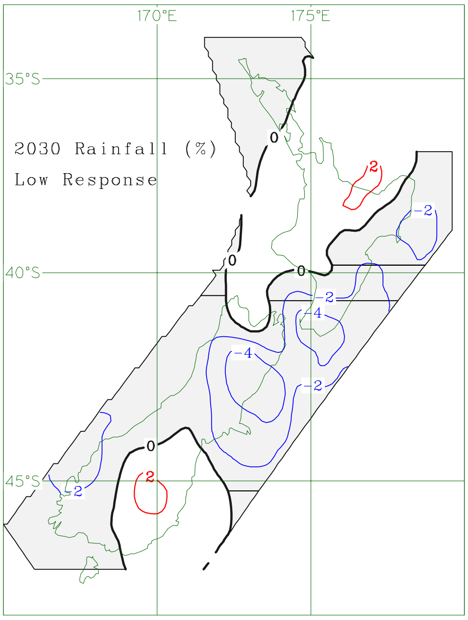


Figure 8. Scenarios of rainfall and temperature sensitivities to global warming.



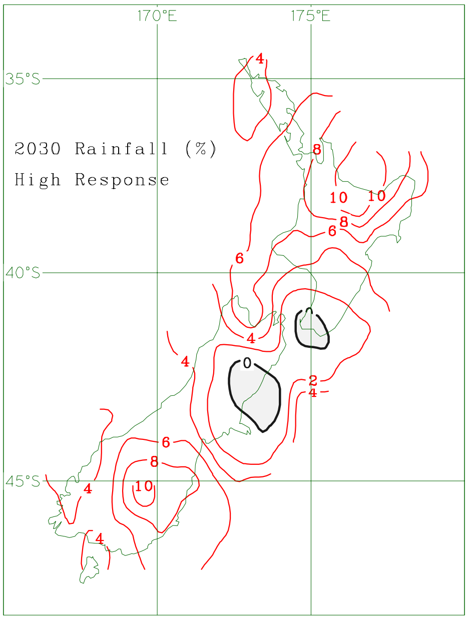
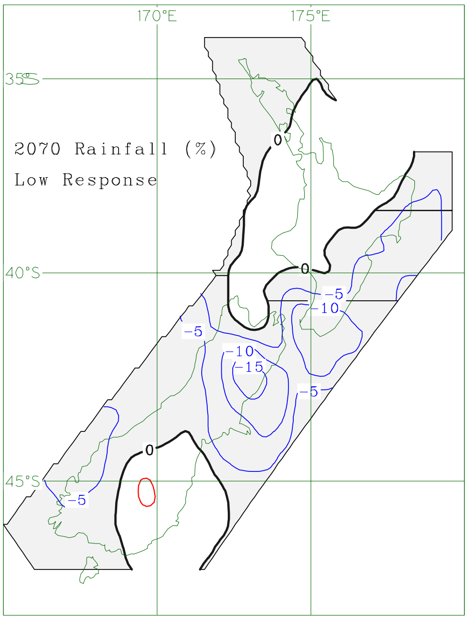


Figure 9. 2030 Low response

Figure 10. 2030 High response



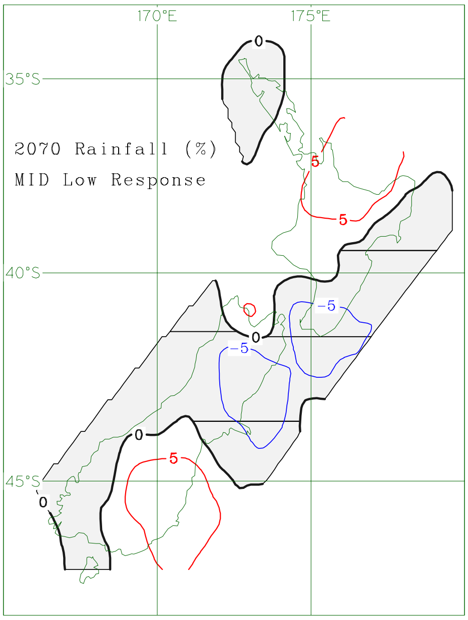


Figure 11. 2070 Low response

Figure 12. 2070 Mid-Low response

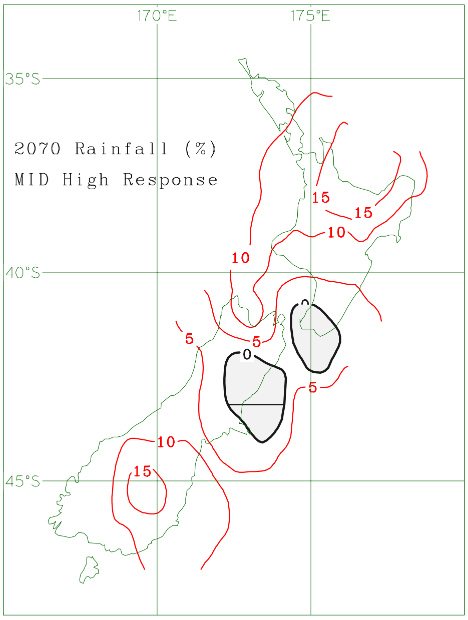


Figure 13. 2070 Mid-High response

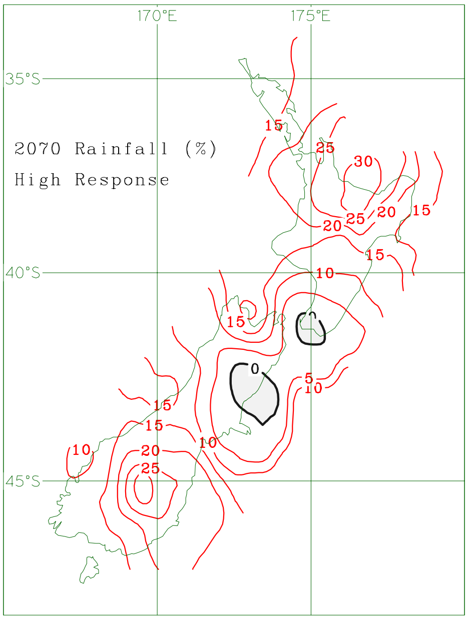


Figure 14. 2070 High response