Changes in drought risk with climate change

NIWA Client Report: WLG2005-23
May 2005

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Executive Summary

As human activity adds more greenhouse gas to the atmosphere, most climate change scenarios predict rising temperatures and decreased rainfall in the east of New Zealand. This means eastern parts of the country are expected to experience more droughts as the 21st century goes on. Our report seeks for the first time to define the possible range of changes in future drought risk.

This report was commissioned because of the importance of drought for agriculture and water resources. The report aims to give central and local government and the agriculture sector an indication of how big future drought changes could be in the various regions. This information can be relevant in managing long-term water resources and land use, including planning for irrigation schemes.

Methods Used

Nobody can predict exactly how much New Zealand's climate will change. Future greenhouse gas concentrations depend on global social and economic development, climate projections differ between models, and natural climate variability adds a further complication. But that is not to say that 'anything goes'. Rather, it means that there is a range of plausible scenarios in response to the question 'How will climate change affect future drought risk?'

In this report we investigate four scenarios, by combining two different global-average temperature projections with two different regional patterns as produced by two climate models. The two global temperature projections span the central portion but not the full range of possible global temperature changes developed by the Intergovernmental Panel on Climate Change for their 2001 Climate Change Assessment. For the models used, the global temperature increase by the 2080s ranges from 1.8°C to 2.9°C. The global models predict trends in broad climate patterns across the Pacific. These are "downscaled" to produce more locally-detailed New Zealand projections, using a statistical technique that accounts for the effect on climate of New Zealand's topography. One model predicts there would be even more rain falling in the west of New Zealand and less in the east than at present. The other model predicts only a small change in the west/east rainfall compared to the present day. Both models predict a general warming of New Zealand, but at a lesser rate than the global average.

In this Summary we highlight just two of these scenarios: a "low-medium" scenario coupling the lower global temperature projection with the downscaled climate model having the small west/east rainfall change, and a "medium-high" scenario which couples the higher global temperature projection with the downscaled model in which the west/east rainfall ratio changes significantly. The low-medium scenario and the medium-high scenario bracket many of the most plausible projections for future New Zealand climate change (including our other two scenarios that are discussed in the main report) and hence provide useful guidance for decision-makers.

Drought is caused by a number of climatic factors, including how much rain falls, how high temperatures are, and how much wind the country experiences. We have used the 'potential evapotranspiration deficit' (*PED*), accumulated over a July to June 'growing year' as our measure of drought. This measure incorporates all three of the above climatic factors. Accumulated *PED* is the amount of water that would need to be added to a crop over a year to prevent loss of production due to water shortage. For pastures not receiving irrigation, an increase in accumulated *PED* of 30 mm corresponds to approximately one week more of pasture moisture deficit (reduced grass growth). In this study, drought *risk* is defined as the probability that a given level of dryness, expressed as accumulated *PED,* is exceeded in any given year.

Key Findings

1. Drought risk is expected to increase during this century in all areas that are currently already drought-prone, under both the 'low-medium' and the 'medium-high' scenarios.

2. Under the 'low-medium' scenario, by the 2080s severe droughts (defined in this report as the *current* one-in-twenty year drought) are projected to occur at least twice as often as currently in the following areas: inland and northern parts of Otago; eastern parts of Canterbury and Marlborough; parts of the Wairarapa; parts of Hawkes Bay; parts of the Bay of Plenty; and parts of Northland (see Figure ES1).

3. Under the 'medium-high' scenario, our results suggest that the frequency of severe drought in these areas could increase even more. By the 2080s, severe droughts are projected to occur more than four times as often in the following regions: eastern parts of North Otago, Canterbury and Marlborough; much of the Wairarapa, Bay of Plenty and Coromandel; most of Gisborne; much of Northland. For many of the other eastern regions, the frequency of severe drought is projected to at least double by the 2080s under this scenario (see Figure ES2).

4. Water deficits in an average year are projected to increase by between about 50 mm and 250 mm *PED* in the driest regions by the 2080s, depending on the climate scenario and location. Annual averages are currently about 300-500 mm *PED* in these areas. In some dry areas, a 200 mm increase in average annual *PED* would mean that a drought of medium severity (such as the 1991/92 drought in Canterbury) could become the yearly norm in those areas by the 2080s.

5. The projected increased *PED* accumulation over the year would probably produce an expansion of droughts into the spring and autumn months. For the 'medium-high' scenario, the drying of pasture in spring is advanced by about a month in the 2080s in dry eastern regions, relative to the present climate.

6. The table below summarises changes in severe drought risk for characteristic locations in some currently drought-prone locations.

Location	Present *PED* (mm) 1 in 20 yr drought	2080s, low-med scenario. *PED*(mm), 1 in 20 yr drought	2080s, med-high scenario. *PED*(mm), 1 in 20 yr drought	2080s, low-med scenario. Average return interval (yrs) for current 1 in 20 yr drought	2080s, med-high scenario. Average return interval (yrs) for current 1 in 20 yr drought
Ranfurly (N. Otago)	645	700	725	8.5	6.5
Darfield (E.Canterbury)	465	515	650	10.5	3.5
Blenheim (E. Marlborough)	895	955	1035	12.0	7.0
Napier (Hawkes Bay)	740	820	1010	9.5	2.5
Whangarei (Northland)	415	465	580	8.0	3.0

We use the 1-in-20 year drought (i.e., a drought that on average occurs only once in 20 years) as the measure for a 'severe' drought. The first three columns of the table provide information on how dry the current and future 1-in-20 year droughts could be. The last two columns indicate how often a drought that *currently* occurs once in 20 years, on average, could occur in future.

Points to bear in mind when reading this report

- Projections of future climate and resulting drought risk, particularly at the regional level, are subject to considerable uncertainty. This report should be taken as a guide to what may happen, rather than a categorical set of predictions. In particular:
  - The New Zealand climate change scenarios used in this report span the central portion but not the full range of IPCC projections of possible global temperature changes (1.4 to 5.8°C by 2100). Thus changes in drought risk which are smaller than those projected under our "low-medium" scenario are possible, particularly if substantial international action is taken to reduce greenhouse gas emissions. Similarly, changes greater than our "medium-high" scenario are also possible.
  - The study utilises projected future daily time-series of rainfall to produce the future *PED* scenarios. These are obtained by adjusting observed daily rainfalls by monthly factors obtained from the downscaled global climate model predictions. This approach assumes there is no change in the number of wet days each month compared to the present climate – just a proportional change in the amount of rain each wet day.
  - Results presented in this report assume that the increase in leaf stomatal resistance to evaporation due to rising carbon dioxide levels is roughly offset by an increase in leaf area. 'Increase in stomatal resistance' refers to the idea that less moisture passes through the minute pores (stomata) in a plant's leaves and stem when there is more CO_2 in the atmosphere. But increased CO_2 concentration will also stimulate leaf growth because CO_2 acts as a fertiliser, so the number of stomata through which moisture can pass increases. We assumed in this report that the two effects cancel each other out. The technical appendix to this report discusses the possible implications of changes in stomatal resistance on the projected changes in drought risk.
- The projected changes are relative to a 1972-2003 baseline, a period probably already somewhat drier in the east than for the 20th century overall because of long-term (20-30 year) natural variation in the climate. This long-period natural variation will continue to influence drought risk from decade to decade, in addition to the changes expected from increased greenhouse gases.
- Our *PED* calculations, and comments on drought frequency, are for unirrigated pasture. Irrigation can in principle offset increases in drought risk where sufficient water for irrigation is available. This report does not address how actual irrigation demand for river or ground water may change in future, or how current water resources might be affected by lower annual rainfall and increased drought frequency. This is a subject on which further research is recommended.
- A 'one-in-twenty-year' or 'twenty year average recurrence interval' event will not normally occur precisely once every twenty years. Over a very long period of time such an event is expected to occur in one twentieth of all years, but any separate individual events may occur closer or further apart in time.
- This report focuses on drought risk, and does not explore possible implications of climate change for heavy rainfall and flooding. The report indicates that many parts of New Zealand are likely to become drier on average, but this is in terms of the moisture availability for pasture growth. It does not necessarily mean the frequency of very heavy rainfall and floods will decrease. Previous research suggests the frequency of very heavy rainfall may in fact increase in many parts of New Zealand, even in those areas where the annual rainfall decreases on average.

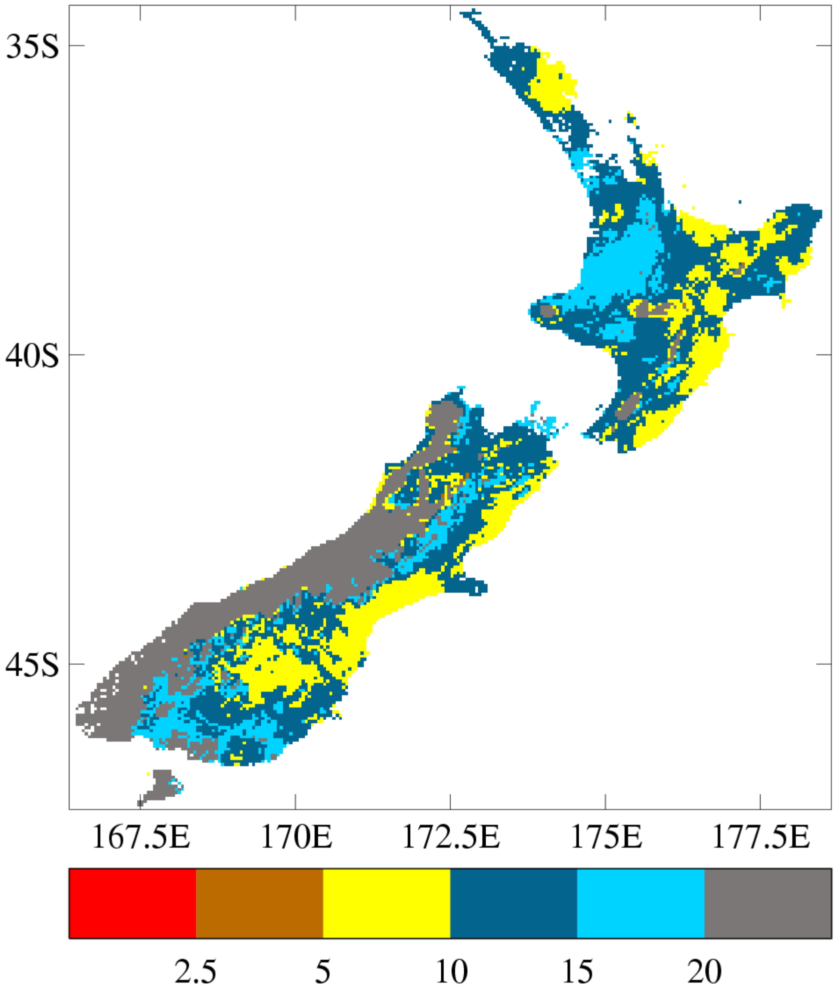

Figure ES1: Predicted average recurrence interval (years) in the 2080s under the 'low-medium' climate scenario, for the driest annual conditions that currently occur on average once every 20 years. The measure used is the *PED* (Potential Evapotranspiration Deficit) accumulated over a growing year (July to June). Example: Timaru is in a yellow region on the map. This means the current one-in-twenty year drought could occur (on average) between once every 5 years, and once every 10 years, in the 2080s under the 'low-medium' scenario (ie, 2 to 4 times more frequently than at present).

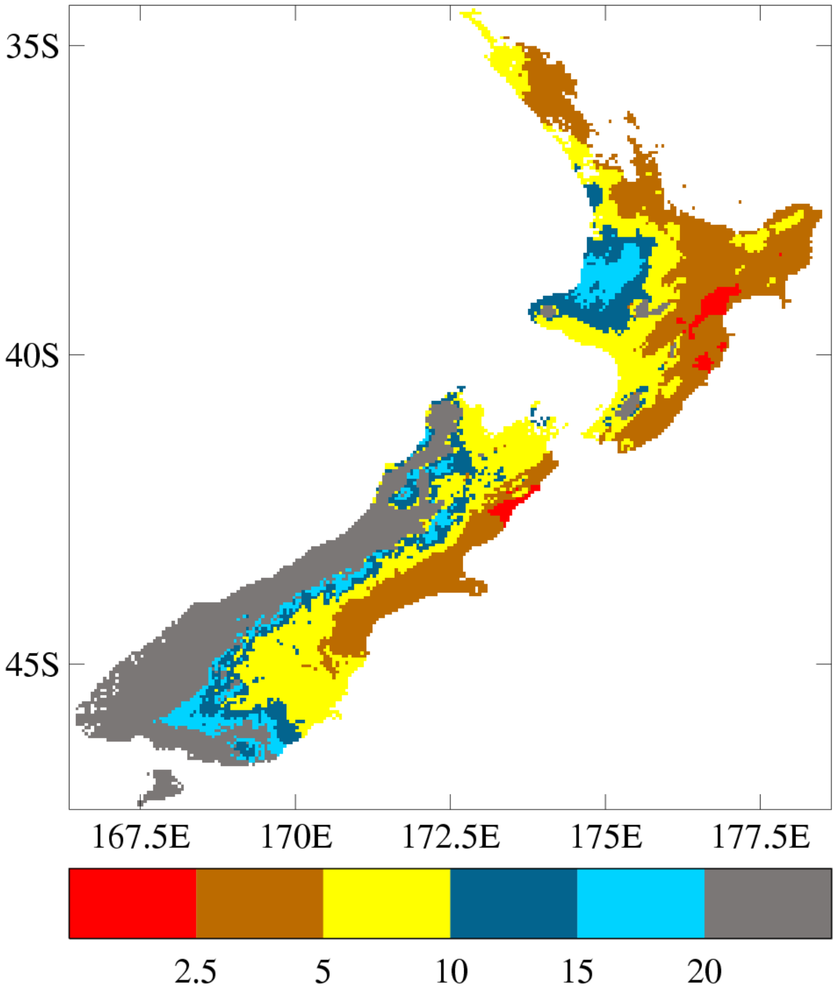

Figure ES2: Predicted average recurrence interval (years) in the 2080s under the ‘medium-high’ climate scenario, for the driest annual conditions that currently occur on average once every 20 years. The measure used is the *PED* (Potential Evapotranspiration Deficit) accumulated over a growing year (July to June). Example: Timaru is in a brown region on the map. This means the current one-in-twenty year drought is predicted to occur (on average) between once every 2.5 years, and once every 5 years, in the 2080s under the ‘medium-high’ scenario (ie, 4 to 8 times more frequently than at present).

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1. Introduction

The purpose of this study is to provide quantitative measures of likely future changes in drought risk in New Zealand under climate change. This report is aimed at central and local government, water managers, and the agriculture sector, for whom the results are relevant when considering long-term management of water resources and land use. It was commissioned by the Climate Change Office of the Ministry for the Environment, and the Ministry of Agriculture and Forestry.

This section of the report describes the background to the drought risk study, introduces the index we use in this report to quantify 'drought', and discusses the use of scenarios to cover the range of possible future changes in drought risk. Section 2 introduces the reader to the historical variability of drought, in both space and time. Section 3 applies the climate change scenarios to project how drought risk might change under global warming. Sections 4 and 5 provide some discussion and a list of references. A technical appendix (Section 6) supplies more detail and additional discussion of issues raised in the main report.

1.1 Background to Drought Risk Study

Human activity is increasing the concentration of greenhouse gases in the atmosphere, and leading to global climate changes (IPCC, 2001). Scenarios of future climate change for New Zealand suggest that rainfall and temperature changes will differ between different parts of the country (Mullan *et al*., 2001; Wratt *et al*., 2003). These changes are expected to increase drought risk for much of New Zealand, and especially the drought-prone eastern regions of the country.

The study was undertaken in two phases. The first phase (see Appendix) was to develop a quantitative indicator of drought risk for this study and apply it to the recorded climate from recent decades to assess how variable and severe droughts can be under the 'current' climate. The second phase (the topic of this report) was to apply the drought risk indicator to a number of climate change scenarios to show a plausible range of effects that climate change may have on drought risk around the country.

1.2 Drought Index: Potential Evapotranspiration Deficit

Key points:

- Drought is caused by a number of climatic factors, including how much rain falls, how high temperatures are, and how much wind the country experiences.
- We use the 'potential evapotranspiration deficit' (*PED*) as our measure of drought. This measure incorporates all three of the above climatic factors.
- Accumulated *PED* is the amount of water that would need to be added to a crop over a year to prevent loss of production due to water shortage. For pastures not receiving irrigation, an increase in accumulated *PED* of 30 mm corresponds to approximately one week more of pasture moisture deficit (reduced grass growth).

- We calculate accumulated *PED* over a July to June 'growing year', from daily information stored in NIWA's climate database.

A consensus emerged from the drought risk workshop held in Phase 1 of this study that a drought index based on potential evapotranspiration deficit (*PED*) would be suitable for assessing changes in drought risk. The method used for calculating *PED* is given in the Appendix (section 6.3) of this report.

PED is measured in millimetres (like rainfall), and can be thought of as the amount (depth) of water we would need to supply a crop, in addition to observed rainfall, to prevent loss of optimum production through water shortage. For example, a *PED* of 200 mm over a growing season could be overcome by applying 200 mm of water at appropriate times through irrigation. The total volume (in cubic metres) of water needed in that case would be: 200 times the paddock area in hectares, times the irrigation efficiency factor, times 10 (to convert to cubic metres).

PED is derived from a water balance model for the topsoil, which accounts for water gain from rainfall and loss from evapotranspiration (Coulter, 1973; Porteous *et al*., 1994). Evapotranspiration is the loss (or consumption) of water from an extended area of a short green crop (e.g., pasture) to the atmosphere through evaporation (from the soil and other surfaces) and transpiration (from plant leaves and stems). *Potential* evapotranspiration (*PET*) refers to the maximum amount of water a crop can consume to meet both its physiological requirements and atmospheric demand when it is well supplied with water. When the crop is short of water at times of low rainfall, a gap develops between the potential water consumption (*PET*) and what the plant is actually consuming because of the dry weather. This gap is referred to as the potential evapotranspiration deficit, or *PED*.

In effect, *PED* is approximately equivalent to the amount of water that would need to be added by rainfall or irrigation to keep pasture growing at its daily potential rate. The Technical Appendix describes the relationship between *PED* and 'days of evapotranspiration deficit', a concept with which farmers are more familiar.

Our method for calculating historical values of *PED* at a particular location requires daily values of rainfall and potential evaporation. We obtained these from a January 1972 – December 2003 data set prepared by NIWA (Tait *et al*., 2005). This uses daily measurements from New Zealand climate observing stations to estimate climate parameters on a 0.05° latitude by 0.05° longitude grid (approximately 5km by 4km) covering the whole country. Daily values of *PED* were accumulated over July to June years, beginning from zero on July 1st each year. These start and end points were chosen because *PED* accumulation is close to zero in the winter months most of the time.

We need to use an accumulated total (not just daily amounts of *PED*) because droughts are the result of dry conditions over a period of time. When discussing *PED* and its changes in this report, we use the July-June accumulated total unless otherwise stated.

1.3 Climate Change Scenarios

Key points:

- There is a range of plausible scenarios in response to the question ‘How will climate change affect drought risk?’
- In this report we use four scenarios for climate change. These combine two different projections for future global-average temperatures with two different regional patterns of change as projected by two global climate models.
- The two projections for future global temperatures we use are approximately 25% and 75% of the way between the lowest and the highest temperature projections developed by the Intergovernmental Panel on Climate Change for their 2001 Climate Change Assessment. In this report, we refer to the lower projection as “25% scaling” and the higher projection as “75% scaling”.
- The global models predict broad climate patterns across the Pacific. We “downscale” these broad patterns to produce more locally-detailed New Zealand projections, using a statistical technique that accounts for the effect on climate of New Zealand’s topography.
- The two global climate models we choose are widely used and scientifically respected. One was developed by the CSIRO, Australia, and one by the UK MetOffice Hadley Centre. When downscaled the Hadley model predicts a larger change in the ratio of western to eastern rainfall in New Zealand (compared to present conditions) than the CSIRO model.
- The four scenarios used in this report represent a range from a “low-medium” scenario (25% IPCC scaling, CSIRO model) to a “medium-high” scenario (75% IPCC scaling, Hadley model).
- We apply our four scenarios to two time periods: the “2030s” (2020-2049) and the “2080s” (2070-2099).

The standard approach to assessing future impacts of climate change is to develop ‘scenarios’ that take account of the range of estimated future emissions of greenhouse gases, and also the variation between models in the projected patterns for the New Zealand region. The global climate models predict trends in broad climate patterns across the Pacific, but do not take account of the effect of New Zealand’s topography on the local climate. The local changes are inferred from the coarser-scale information of the global climate models by a statistical technique known as ‘downscaling’.

Statistical downscaling starts with historical observations, and calculates “downscaling relationships” between broad regional climate patterns and these local climate observations. The downscaling relationships are then applied to the broad future regional patterns predicted by the global models, in order to provide more locally-detailed projections for New Zealand (e.g. Mullan *et al*., 2001). In the present study, we use the gridded New Zealand January 1972 – December 2003 data set described in Section 1.2 to build up historical relationships between monthly broad-scale climate patterns and local monthly rainfall and *PET* at locations on the 0.05° latitude by 0.05° longitude grid. These relationships are then applied to projected monthly regional climate patterns from a particular global climate model for the

"2030s" (defined as the period 2020-2049) and the "2080s" (2070-2099). The result is a set of monthly rainfall and *PET* projections for each of these periods, downscaled from the global model to each location on the grid.

Two global climate models were chosen for developing these future scenarios: a CSIRO model (known as CSIRO Mark 2), and a model from the UK MetOffice Hadley Centre (known as HadCM2, but referred to as 'Hadley' in this report). These models have been used in previous New Zealand climate change work (eg, Wratt *et al.,* 2003), and have similar global-average temperature changes. However, their downscaled climate changes for New Zealand are rather different. The downscaled Hadley model predicts that New Zealand's east will get even warmer and drier in future compared with the west. The CSIRO model, on the other hand, has a larger (but geographically more uniform) temperature increase over the country but a smaller change in the west to east rainfall difference.

The next step is to adjust the modelled climate changes to be consistent with global temperature projections from the Intergovernmental Panel on Climate Change Third Assessment report (IPCC, 2001), through a procedure outlined in Wratt *et al.* (2003). The IPCC concluded that by 2100 the global mean surface temperature could increase by between 1.4°C and 5.8°C. In the present study we produced two projections for each global climate model we used. The first corresponds to a global temperature change 25% of the way between the lower and upper bounds of the IPCC range, and the second to a global temperature change 75% of the way across this range (see Appendix 6.6 for details). This choice reflects the fact that some climate scientists consider the extremes of the IPCC range to be less likely than the intermediate values (e.g., Wigley and Raper, 2001). Although the low probability extreme values are driving the international debate about "dangerous" climate change, we did not wish to emphasise the extremes in this report.

To summarise: Four scenarios are developed from a combination of two climate models (which produce different patterns of change at the local scale) and two scalings (to account for differences in global emissions and temperature response). The four scenarios (Table 1.1) represent a range from a "low-medium" scenario (25% IPCC scaling, CSIRO model) to a "medium-high" scenario (75% IPCC scaling, Hadley model). However changes in drought risk which are smaller than those projected under our "low-medium" scenario are possible, particularly if substantial international action is taken to reduce greenhouse gas emissions. Similarly, changes greater than our "medium-high" scenario are also possible.

Table 1.1 Four scenarios of future climate change examined in this study.

	Global temperature projection	
Model	**25% IPCC**	**75% IPCC**
CSIRO	2030s, 2080s 'low-medium'	2030s, 2080s
Hadley	2030s, 2080s	2030s, 2080s 'medium-high'

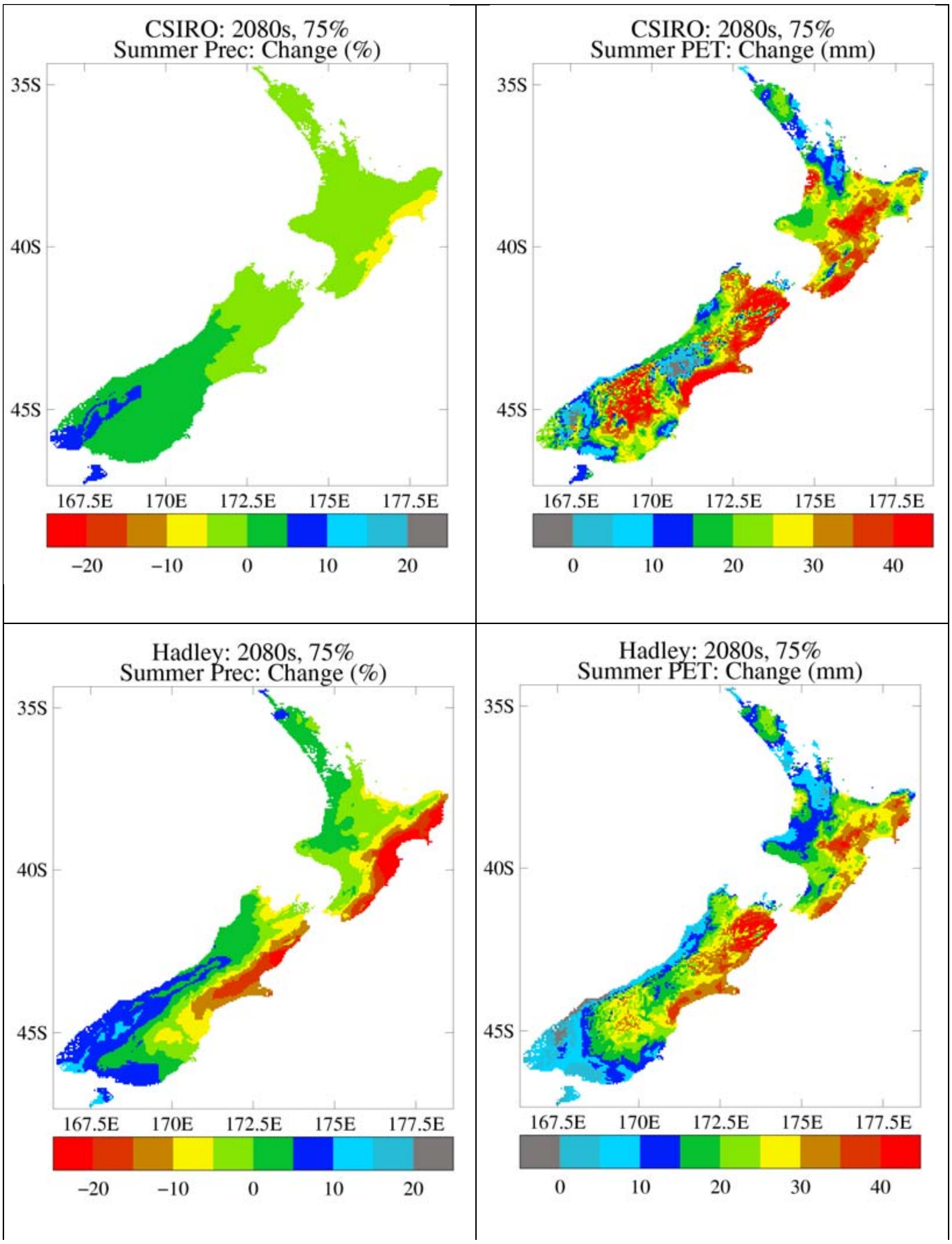


Figure 1.1 **Climate change scenarios for the 2080s, with 75% IPCC scaling, for summer precipitation (%) and summer total potential evapotranspiration (mm), from downscaling the CSIRO and Hadley model output.**

The scenarios provide monthly average changes of rainfall and *PET* at each location on the 0.05° New Zealand grid for the 2030s and the 2080s. We also have daily values at these grid points from the historical 1972-2003 analysis described in Section 1.2. We can therefore produce a hypothetical daily time series of future rainfall at each grid point by multiplying each daily rainfall from the historical record by a monthly adjustment factor equal to the ratio of the projected future rainfall to the observed rainfall for that month. This adjustment procedure leaves unchanged the number of wet days per month, and the year-to-year variability in monthly rainfall, relative to the present climate. Daily grid point values of *PET* for a particular month are assumed to equal the projected average *PET* value for that month (day to day *PET* variations within a month have little effect on accumulated *PED*).

Finally, these projected daily grid point values of rainfall and *PET* are used as input to a water balance calculation to obtain daily *PED* values at the grid points, which are accumulated over July-June years to produce annual *PED* projections for the 2030s or 2080s.

Figure 1.1 shows the change in summer precipitation and *PET* for the CSIRO and Hadley models, as determined for the 2080s with the 75% IPCC scaling. The pattern of change for 25% IPCC scaling is identical to that of 75% scaling, but the amount of change is smaller. The 2030s changes are, in general, similar but weaker than the 2080s, particularly in the case of the Hadley model. The CSIRO model tends to weaken the westerlies over New Zealand in the first 50 years (to 2030s) and thereafter strengthen them (Mullan *et al.* 2001), so the 2030s pattern can differ from that for the 2080s.

Summer is chosen for this example, as the hottest time of year with the highest evaporation. The projected summer precipitation changes are similar in pattern, but quite different in size, for the two models. The Hadley model projects large precipitation decreases in the drought-prone eastern regions, in all seasons of the year. The CSIRO model has small precipitation decreases in the east, in spring and summer. In winter (not shown), the CSIRO model projects large precipitation *increases* in the east, but this is not a critical time of year for drought.

The *PET* changes are much more similar for the two models, in spite of the greater warming by the CSIRO model. In the Hadley model, the increase in windiness compensates for the smaller warming. Over the whole year for the 75% scaling projections (not shown), total *PET* increases by about 100mm or more in the currently driest eastern parts of New Zealand. Thus, in the east of the country, there is both a decrease in precipitation and an increase in evaporation during the warmest seasons, which we would expect to aggravate the current tendency for droughts in this region.

2. Drought Risk under Current Climate

Key Points:

- In order to quantify the likely effects of climate *change* on drought risk around the country, we must first provide quantitative estimates of the *current* drought risk.
- The driest parts of the country (Gisborne, Hawkes Bay, Marlborough, most of coastal Canterbury, and inland Otago) experience annual water deficits in the 300-500mm range. The average annual *PED* in coastal Marlborough can exceed 600mm.

- The incidence of drought varies from year to year. El Niño tends to bring drier conditions to the northeast of both the North Island and the South Island. La Niña can also bring drought to the eastern South Island.

2.1 Typical Levels of Potential Evapotranspiration Deficit

In this report we measure the incidence and severity of droughts in New Zealand in terms of the potential evapotranspiration deficit (*PED*). As we explained in section 1.2, *PED* was calculated daily on the 0.05° national grid, and accumulated for each calendar month over the 31-year period July 1972 to June 2003. Figure 2.1 (left panel) shows the total July to June *PED* averaged over the 31 years of gridded data. In the wettest regions of the West Coast and at high altitude, annual *PED* is close to zero, meaning that at no time of year is there a pasture deficit. The driest parts of the country (Gisborne, Hawkes Bay, Marlborough, most of coastal Canterbury, and inland Otago) experience annual deficits in the 300-500mm range (green shading), except for the coastal tip of Marlborough where calculations suggest the average annual *PED* could exceed 600mm.

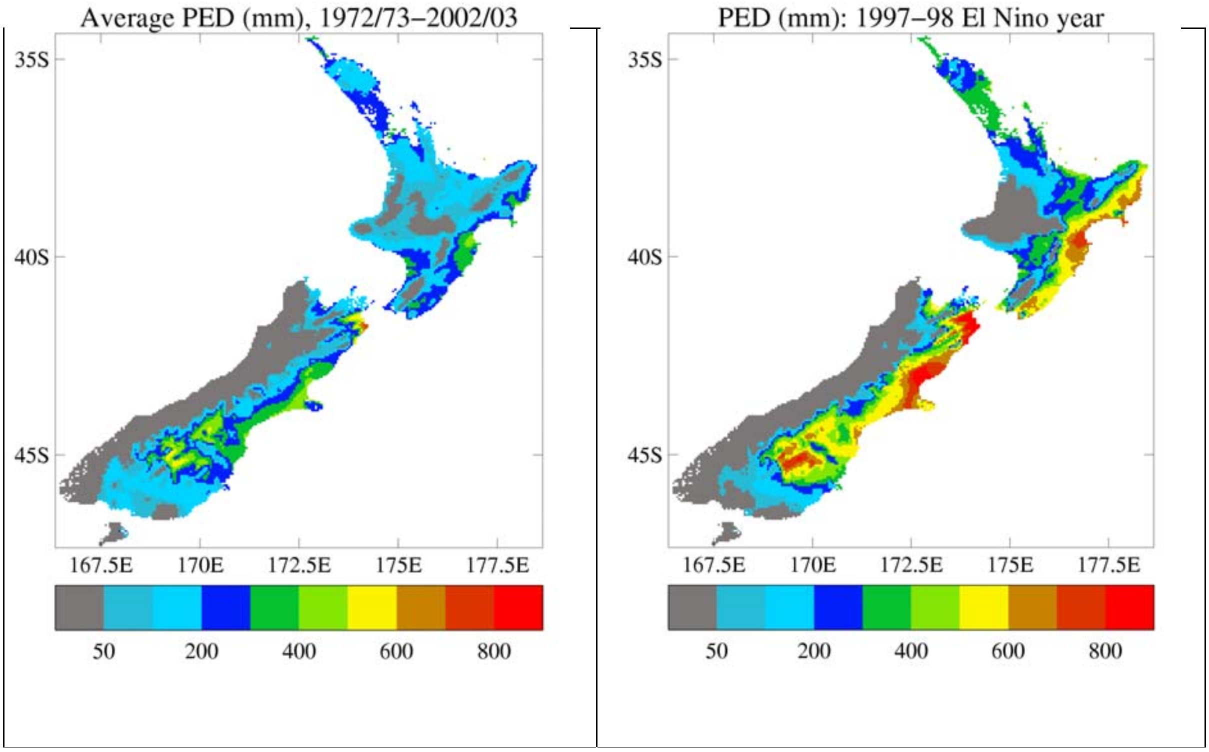


Figure 2.1 Accumulated July-June *PED* (mm) calculated from 0.05° gridded data set: average over 31-year period 1972/73 to 2002/03 (left), and *PED* levels in extreme drought year of 1997/98 El Niño (right).

2.2 Year to Year Variability in Drought

Drought incidence will vary from year to year, and is often associated with El Niño-Southern Oscillation (ENSO) variations. ENSO is a natural fluctuation of the tropical Pacific atmosphere and ocean. In the El Niño phase, the easterly tropical trade winds weaken and tropical sea surface temperatures can be several degrees above normal. New Zealand often experiences stronger than normal southwesterly airflow, with lower temperatures across the country and drier conditions in the northeast of both Islands. The La Niña phase results in higher pressures and more settled weather over southern New Zealand, which can also bring drought to the eastern South Island.

Figure 2.1 (right panel) shows that *PED* exceeded 600 mm in a substantial part of eastern New Zealand in the severe drought year of 1997/98, which coincided with a strong El Niño in the tropical Pacific. Drought can affect different parts of the country in different years. Figure 2.2 suggests one way to get an integrated national picture of historical drought severity: time series of the percentage of gridpoints with *PED* exceeding some specified level immediately highlight the years of widespread drought. The big El Niño years of 1972/73, 1977/78 and 1997/98 stand out.

Clearly, any ranking of drought severity requires specifying a *PED* threshold. Drought impacts cannot be easily related to a uniform *PED* threshold across the country, since many eastern regions experience a *PED* of more than 200mm almost every year, and local farmers have adapted their operations to this. However, this same level of dryness might well impact adversely on farming operations in other, normally wet parts of the country (e.g. Manawatu). It can nonetheless be useful to plot the total area of the country that exceeds any set of thresholds (e.g. *PED* levels of 200, 400 and 600mm in Figure 2.2) as an indication of how widespread drought conditions were in any given year. For an annual *PED* accumulation of 400mm or more, there were 9 years out of the 31-year historical record, where more than 10% of the country was "in drought". These years, in decreasing order of severity, were: 1997/98, 1972/73, 1977/78, 2000/01, 1982/83 and 1988/89, 2002/03, 1981/82, and 1984/85.

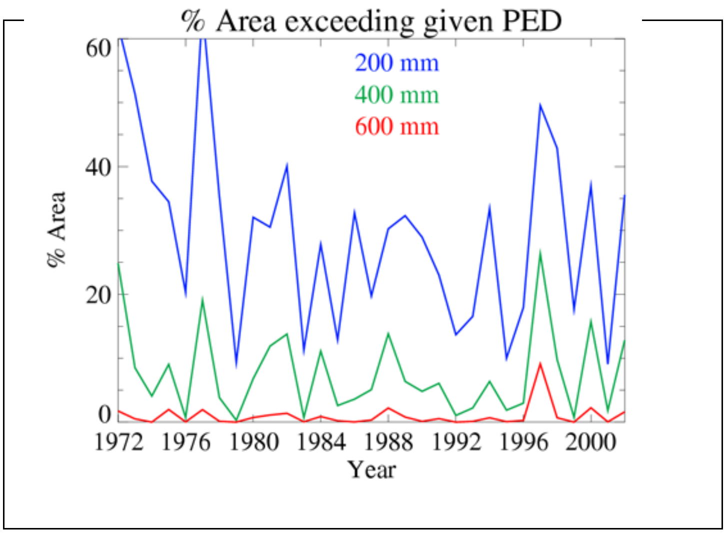


Figure 2.2 Fraction of gridpoints (on 0.05° grid) with July-June *PED* accumulation exceeding specified threshold. The time series highlights the severe droughts.

2.3 Statistics of Current Drought Risk

There are various ways in which drought incidence can be characterised statistically. In this report we focus primarily on drought *intensity* (the level of *PED* that is reached in a given year and location) and drought *risk* (the probability that a given level of *PED* is exceeded in a given year at a given location). However, drought *duration* is also an important issue in dry-land farming. There is of course a fairly strong link between drought intensity and duration, with stronger droughts generally lasting longer.

We can also analyse annual drought risk in terms of its *return period*. The return period of an event is defined as the inverse of its exceedance probability: thus,

$$\text{Return Period} \qquad T = \frac{1}{P(X > x_T)}$$

where the variable X is drought intensity (in mm *PED*), P indicates probability, and x_T is the magnitude of a drought having a return period of T. For example, if there was a 5% chance (0.05 probability) of annual *PED* exceeding 600mm, then we would say that event (*PED* of more than 600 mm) has a return period of 20 years. Note that a 'one-in-twenty-year' or 'twenty-year average recurrence interval' event will not occur precisely at 20-year intervals. The numerical method we have used for estimating return periods is detailed in the Technical Appendix.

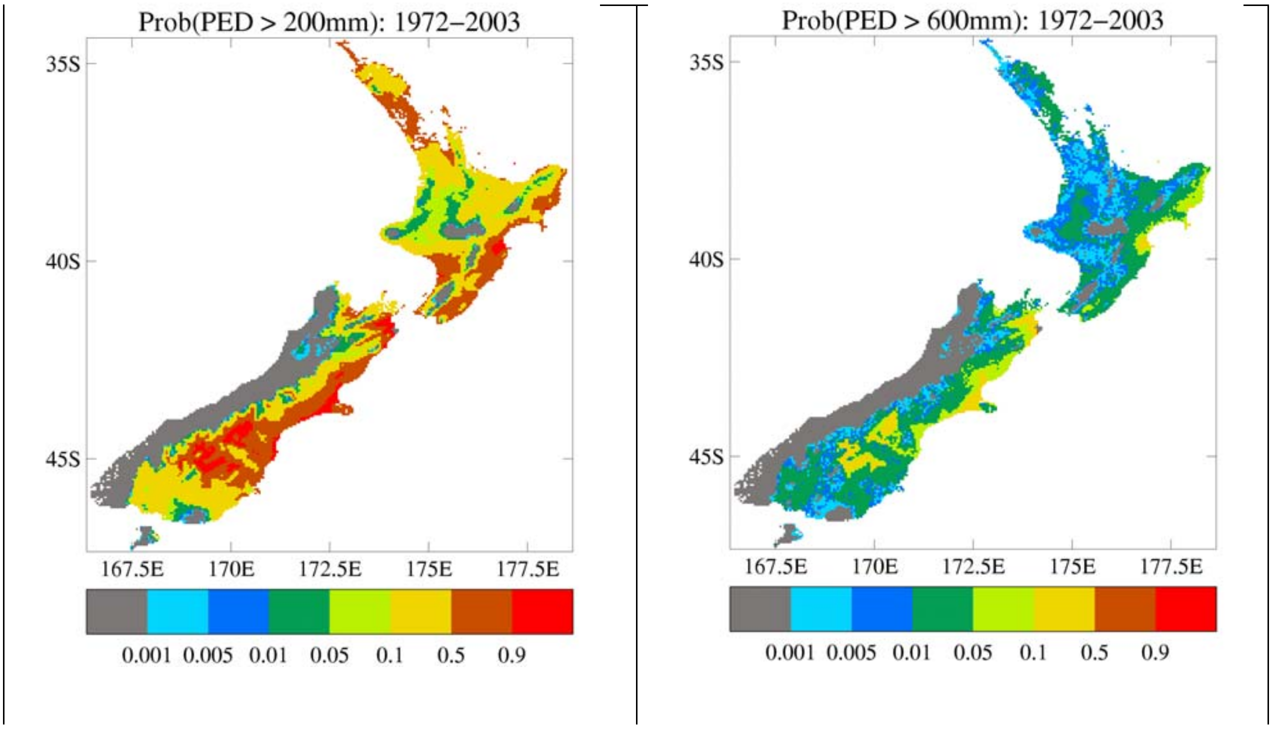


Figure 2.3 **Probability that in any one year the annual accumulated *PED* will exceed 200 mm (left) and 600 mm (right). The inverse of the probability gives the return period of the specified deficit. For example, a probability of 0.05 corresponds to a return period of 20 years.**

2.3.1 Probabilities of Selected Levels of Drought Index

Figure 2.3 shows the probability that *PED* will be more than 200mm (left) and 600mm (right) over New Zealand. (A threshold of 400mm was also used – see Appendix 6.8). In the dry eastern regions, a *PED* of 200mm corresponds approximately to about 1.5-2 months of deficit, and 600mm to 5 months. The regions most susceptible to droughts appear as brown-red shading in the left box of Figure 2.3, where the probability of at least 200m *PED* deficit exceeds 0.5; ie, at least 1 year in every 2 we would expect a deficit of 200mm to be exceeded, and pasture to have insufficient moisture for optimum growth for up to 2 months over the summer period. From the right-hand panel of Figure 2.3, *PED* exceeding 600mm is a 1-in-20 year event at the boundary between the dark green and light green shading.

2.3.2 1-in-20 Year Return Period

In this report, we use a 1-in-20 year *PED* as a convenient measure of 'severe drought', even while recognising that in wetter parts of the country a 1-in-20 year event is not that dry in absolute terms. Rather than mapping probabilities (as in Fig 2.3), we could map return periods. Figure 2.4 shows the *PED* levels corresponding to a 1-in-20 year return period. This gives us a picture of just how extreme droughts can become under the current climate. The 1-in-20 year return period *PED*s for the Lincoln and Napier gridpoints are 770mm and 748mm, respectively. The most extreme individual years in the 1972/73 to 2002/03 data recorded a *PED* deficit of 851mm (in 1988/89) at Lincoln, and 799mm (1997/98) at Napier. During these extreme years, pasture was in moisture deficit for 192 days at Lincoln and 174 days at Napier.

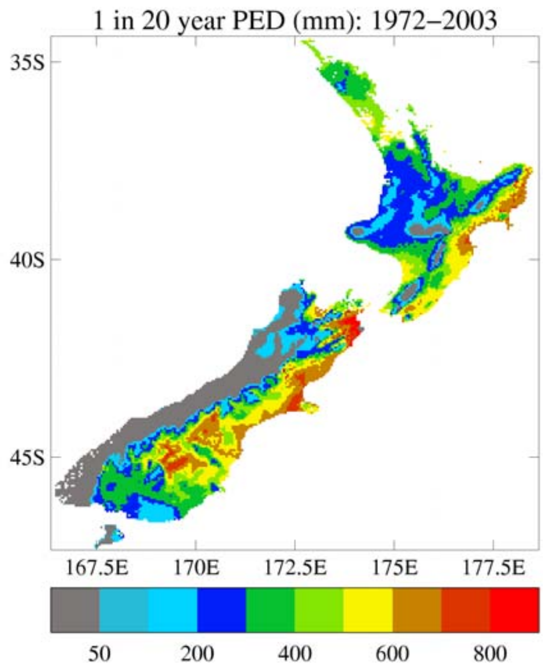


Figure 2.4 ***PED* (mm) with a 1 in 20 year return period, equivalent to a 5% chance (or probability of 0.05) of occurrence in any one year.**

3. Drought Risk under Scenarios of Climate Change

Key Points:

- Under all our climate change scenarios, average annual *PED* increases across virtually the entire country (that is, it gets drier), except for the South Island west coast, by the 2030s. Average annual *PED* increases even more by the 2080s.
- The risk of drought (extreme *PED*) increases in most eastern parts of the country – areas that are drought-prone already.
- Under all our climate change scenarios, a 1-in-20 year drought in eastern regions becomes more common in future. By the 2080s, the frequency of a current 1-in-20 year *PED* increases between two and more than fourfold, depending on the scenario. That is, a drought that currently occurs once in 20 years on average could become a 1-in-10 year, or even a 1-in-5 year, event in that same area.
- The areas where drought risk is projected to increase significantly include parts of North Otago, Canterbury, Marlborough, Wairarapa, Hawkes Bay, Bay of Plenty, and Northland.
- Because all the scenarios predict increased *PED* accumulation over the course of a year, drought periods are likely to 'expand' into spring and autumn more often than currently. In our most severe (medium-high) scenario, the drying of pasture in spring is advanced by about a month in the 2080s in dry eastern regions, compared to the current climate.

3.1 Change in Average Potential Evapotranspiration Deficit

The key result is that average annual *PED* increases across virtually the entire country, except on the South Island west coast, under all scenarios. As expected, the drying tendency increases with time, so is greater in the 2080s than the 2030s, and is larger under the scenarios which assume higher global temperatures (i.e., for 75% scaling than for 25% scaling). The drying tendency is also more extreme for the Hadley model than for the CSIRO projections, as expected from the much greater rainfall reductions in the east in the Hadley model (Figure 1.1). The changes are most significant in already dry eastern regions.

There are, of course, seasonal and regional differences, and quite large intensity differences, between the simulated drought occurrences of the CSIRO and Hadley models. However, the integrated effect of both precipitation and *PET* changes on drought occurrence is relatively uniform, which gives us confidence in our findings.

Figure 3.1 shows the most extreme result for the two models (ie, 2080s, 75% scaling). The CSIRO model projects an increase in *PED* of at least 90mm (average increase of about 3 weeks in length of pasture deficit) over the already dry eastern parts of New Zealand by the 2080s. In the Hadley simulation, the *PED* increase shows the same geographic pattern but with *PED* increases of over 180mm common throughout eastern regions. The Hadley model also suggests the drying effect is stronger in the North Island, which is consistent with the model's larger reduction in precipitation at lower latitudes (Figure 1.1).

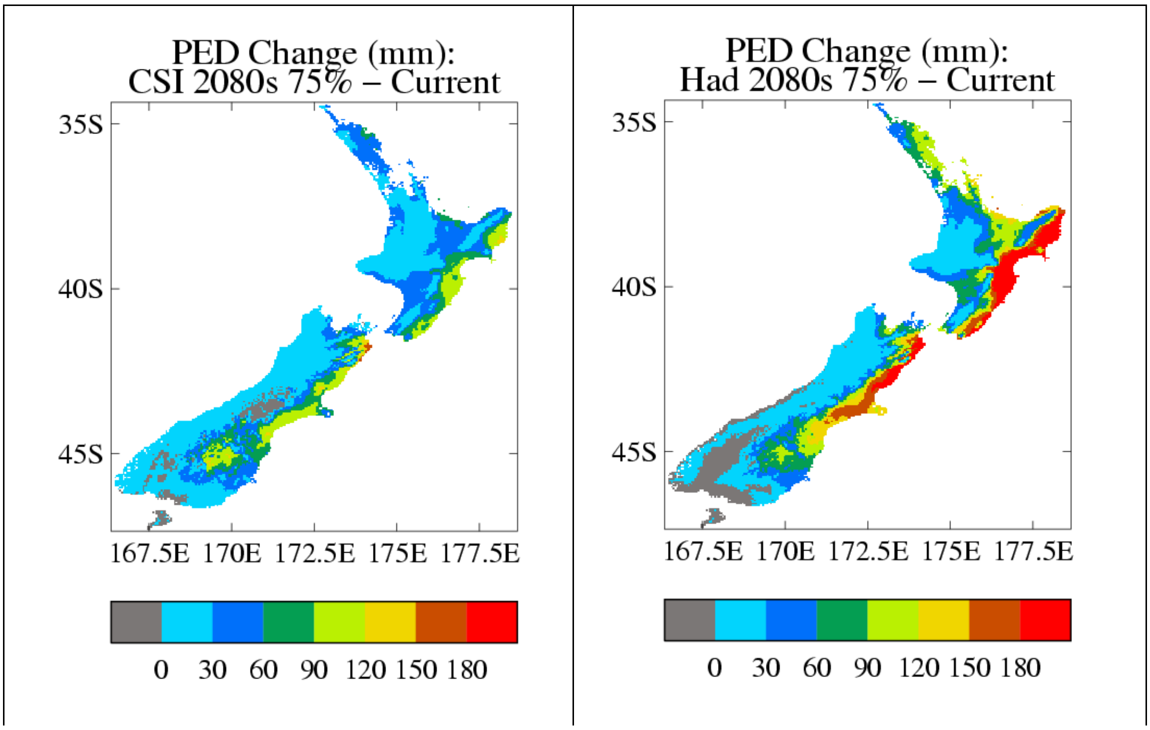


Figure 3.1 Average change in annual accumulated *PED* (in mm) between the current climatology and projected climatology for the 2080s according to the CSIRO (left) and Hadley (right) models, scaled to the IPCC 75% global warming. The contour intervals, every 30mm, correspond approximately to one week of pasture evapotranspiration deficit in summer.

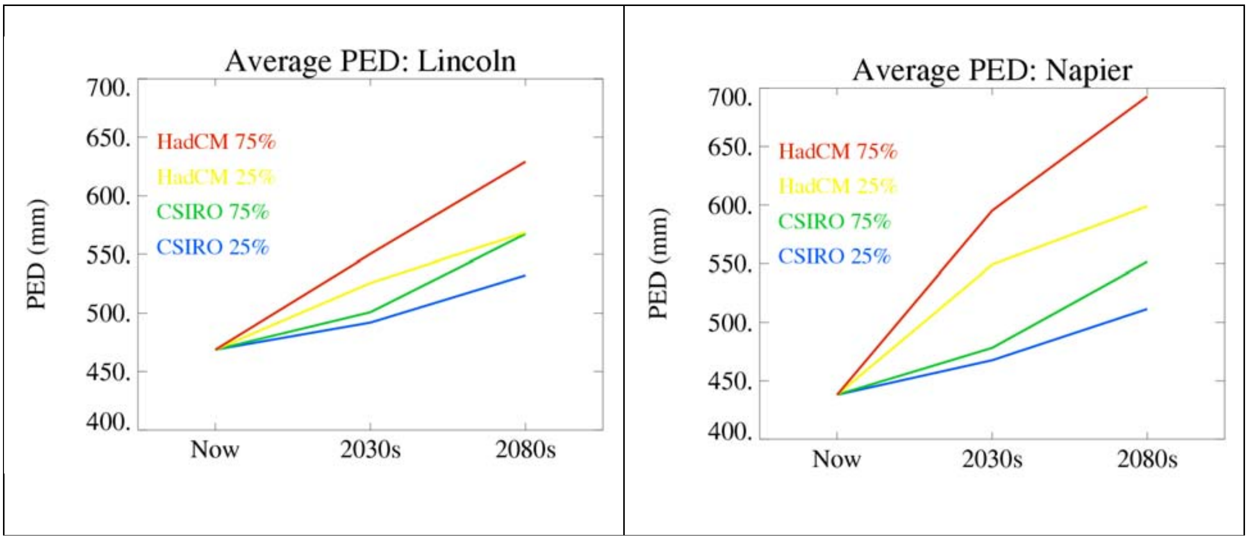


Figure 3.2 Average annual accumulated *PED* (in mm) at two gridpoints corresponding to Lincoln and Napier. Results are shown for the current climate ("Now"), the 2030s, and the 2080s, for four climate change scenarios.

Figure 3.2 show line plots of *PED* levels at the Lincoln and Napier gridpoints. (Mapped changes for the other scenarios are provided in the Appendix (section 6.9)). For the most benign scenario of CSIRO 25% scaling, the average annual *PED* increases at Lincoln from 469mm to 532mm by the 2080s, an increase of more than 2 weeks in restricted pasture growth. The same holds at Napier, where average annual *PED* rises from the present 438mm to 511 by the 2080s. For the most extreme scenario of Hadley 75% scaling, the average annual *PED* by the 2080s is 629mm at Lincoln and 693mm at Napier, suggesting an additional 6 weeks or more of reduced pasture growth in an average year.

Overall, water deficits in an average year are projected to increase by between about 50 mm and 250 mm *PED* in the driest regions by the 2080s, depending on the climate scenario and location. To put this in context: annual averages are currently about 300–500 mm *PED* in these areas. In some dry areas, a 200 mm increase in average annual *PED* would mean that a drought of medium severity (such as the 1991/92 drought in Canterbury) could become the norm in those areas by the 2080s.

3.2 Changes in Drought Risk

3.2.1 Change in Extreme Potential Evapotranspiration Deficit

Along with the increase in average *PED*, there is a corresponding increase in the risk of drought (or extreme *PED*) in most eastern parts of the country. Figure 3.3 shows the projected changes in the 1-in-20 year *PED*, and the probability of *PED* exceeding 600mm. Time series plots are shown for all scenarios at the Lincoln and Napier gridpoints (see Appendix 6.9 for maps of whole country). The 1-in-20 year *PED* (upper panels of Figure 3.3) is very similar in shape to the average *PED* (Figure 3.2). Typically, the 1-in-20 year *PED* is about 300mm higher than the climatological average at both sites, and this difference remains fairly constant for all scenarios.

The lower panels of Figure 3.3 show how the probability of at least 600mm annual *PED* accumulation varies with the scenario. Again, the Hadley model shows more extreme changes in time (the Hadley change at the 2030s is comparable to the CSIRO change by the 2080s) and a more extreme North Island change than South Island one.

3.2.2 Change in Return Period

An alternative way of describing the changes in drought risk is to calculate what the future return period is for a *PED* value that currently occurs with a 1-in-20 year return period. That is, if we consider this level (1 in 20 years) to be a significant anomaly over the growing season (and it will certainly be a severe drought in the east), how much more common will it become?

The results are shown in Figure 3.4 for the four scenarios of the 2080s, where the current 1-in-20 year drought becomes more common everywhere that is not shaded grey. At the boundary between dark blue and yellow, the future return period is 10 years; here, a current 1-in-20 year dry event becomes twice as likely in the future scenario. At the yellow-brown boundary, the event becomes four times as likely (every 5 years on average, instead of every 20).

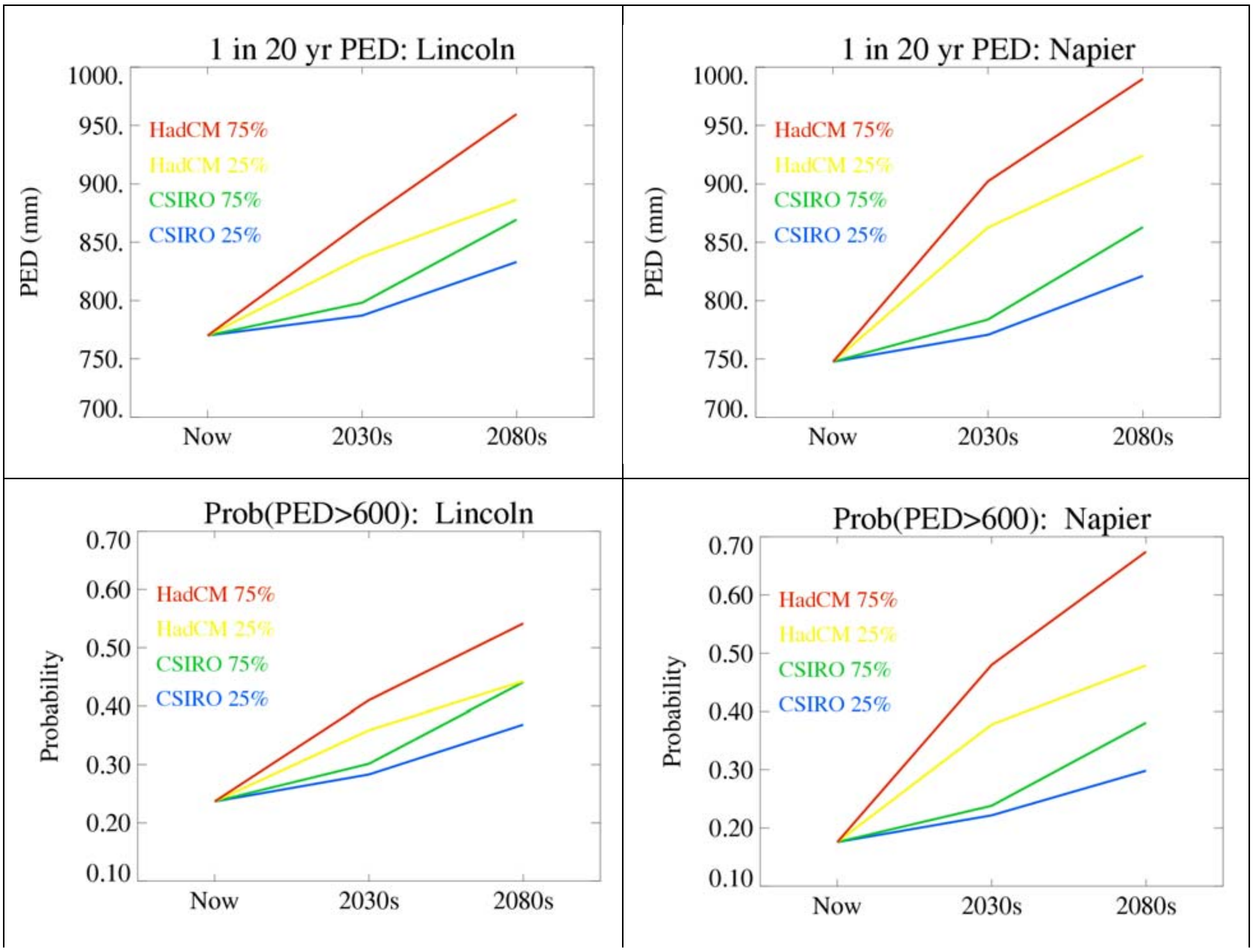


Figure 3.3 **Scenario variation of annual *PED* at the Lincoln and Napier gridpoints. Results are shown for the current climate ("Now"), the 2030s, and the 2080s, for four scenarios. The two upper panels show *PED* levels with a 1-in-20 year return period (5% chance of occurrence in any one year), and the two lower panels show probabilities of annual *PED* exceeding 600mm. For context, the worst droughts in the recent historical record had 851mm *PED* at Lincoln (in 1988/89), and 799mm at Napier (1997/98).**

Under the 'low-medium' scenario (25% scaling, CSIRO model) by the 2080s, severe droughts are projected to occur at least twice as often as currently in the following areas: inland and northern parts of Otago; eastern parts of Canterbury and Marlborough; part of the Wairarapa; parts of Hawkes Bay; parts of the Bay of Plenty; and parts of Northland.

Under the 'medium-high' scenario (75% scaling, Hadley model), by the 2080s, severe droughts are projected to occur more than four times as often in the following regions: eastern parts of the North Otago, Canterbury and Marlborough; much of the Wairarapa, Bay of Plenty, and Coromandel; most of Gisborne; much of Northland. For many of the other eastern regions, the frequency of severe drought is projected to at least double by the 2080s under this scenario.

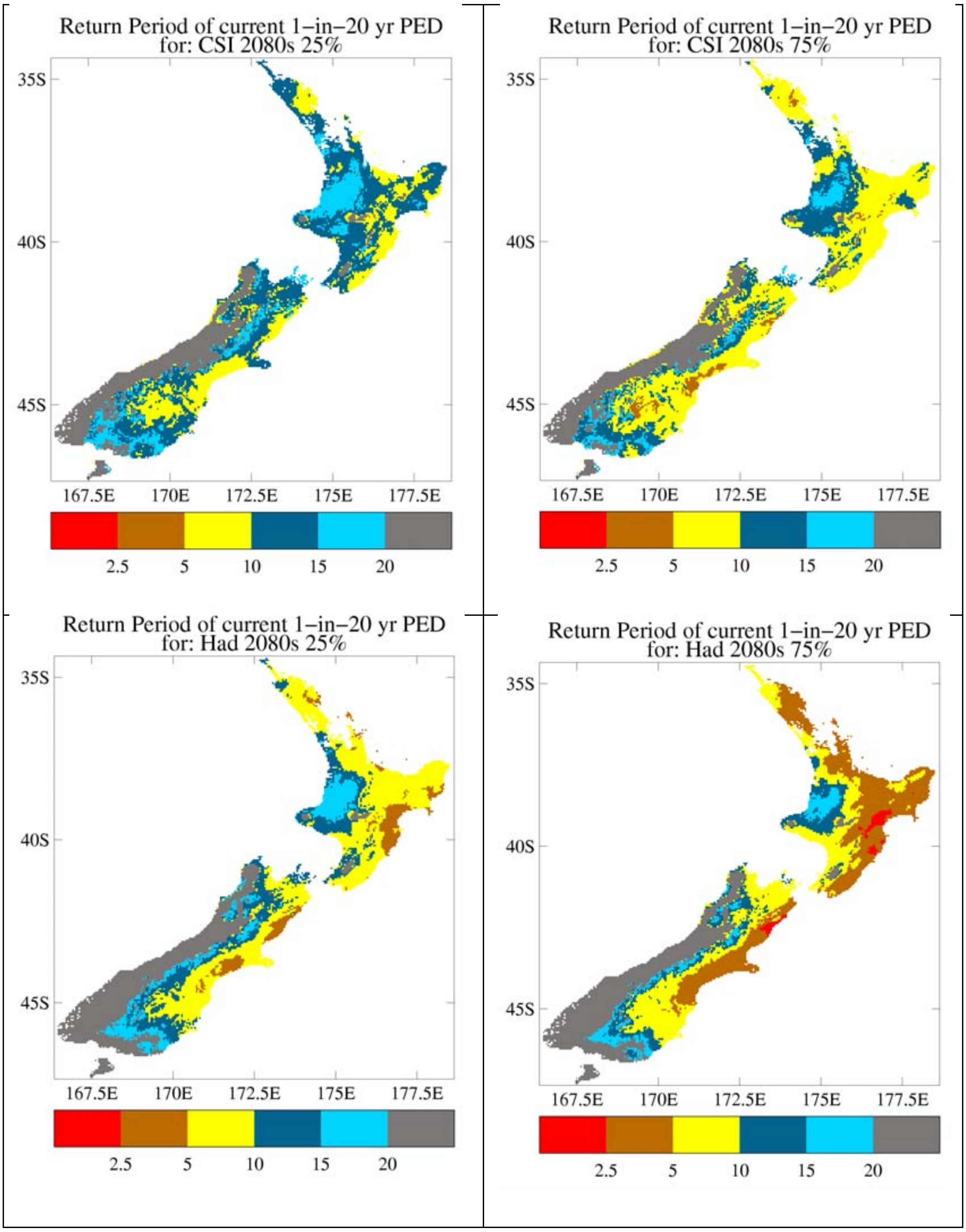


Figure 3.4: Future return periods (years) of current climate 1-in-20 year *PED* events, for four scenarios: CSIRO 2080s 25% and 75% scaling (upper panels) and Hadley 2080s 25% and 75% scaling (lower panels). Grey areas indicate regions of very low drought risk (where return period can't be estimated) and/or regions where drought risk decreases.

The table below summarises changes in severe drought risk by the 2080s for characteristic locations in some currently drought-prone locations. The other two scenarios for the 2080s not given in Table 3.1 (ie, CSIRO 75% and Hadley 25%) are intermediate between the two scenarios shown.

Table 3.1: Present drought risk, and future changes in 2080s for CSIRO 25% and Hadley 75% scenarios, at selected locations. The first three columns of the table provide information on how dry the current and future 1-in-20 year droughts could be. The last two columns indicate how often a drought that *currently* occurs only about once in 20 years could occur in future.

Location	Present climate *PED* (mm) for 1-in-20 year drought	2080s CSIRO 25% scenario *PED*(mm) for 1-in-20 year drought	2080s Hadley 75% scenario *PED*(mm) for 1-in-20 year drought	2080s CSIRO 25% scenario. Average return interval (years) for current 1 in 20 yr drought	2080s Hadley 75% scenario. Average return interval (years) for current 1 in 20 yr drought
Ranfurly (N. Otago)	645	700	725	8.5	6.5
Darfield (E.Canterbury)	465	515	650	10.5	3.5
Blenheim (E. Marlborough)	895	955	1035	12.0	7.0
Napier (Hawkes Bay)	740	820	1010	9.5	2.5
Whangarei (Northland)	415	465	580	8.0	3.0

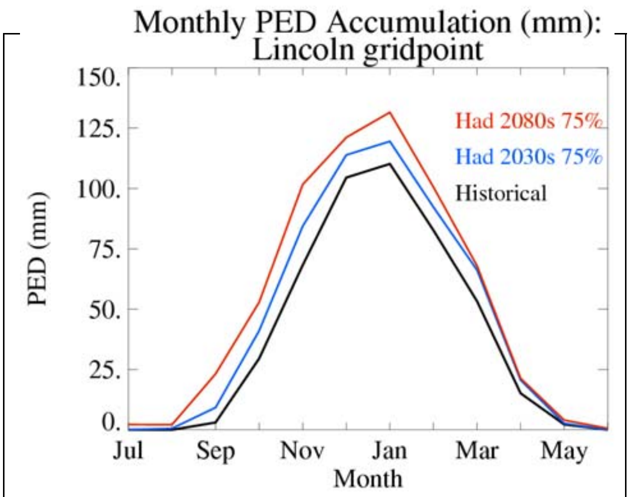
Similar maps of return period changes by the 2030s are given in the Appendix (section 6.9). It needs to be recognised that natural variations in climate on the decadal time-scale can also affect drought incidence. The importance of natural variations, relative to those caused by anthropogenic change, decreases the further ahead in time one goes.

3.2.3 Overseas studies of changes in drought under global warming

There have been a large number of international studies of changes in water availability under global warming. We have been unable to find a study that is truly comparable to ours in terms of using *PED* as a quantitative indicator of changes in drought risk, and calculating return period changes for drought. Nonetheless, overseas studies have found comparable changes in water resources (runoff or some other measure). They are discussed in more detail in the Appendix (section 6.12).

3.2.4 Change in Seasonality of Future Drought

Figure 3.5 illustrates another aspect of drought change at the Lincoln and Napier gridpoints. The figure shows *monthly PED* accumulation for the Hadley 75% scenario. This scenario is the most extreme; all other scenarios show the same direction of change but are less pronounced.



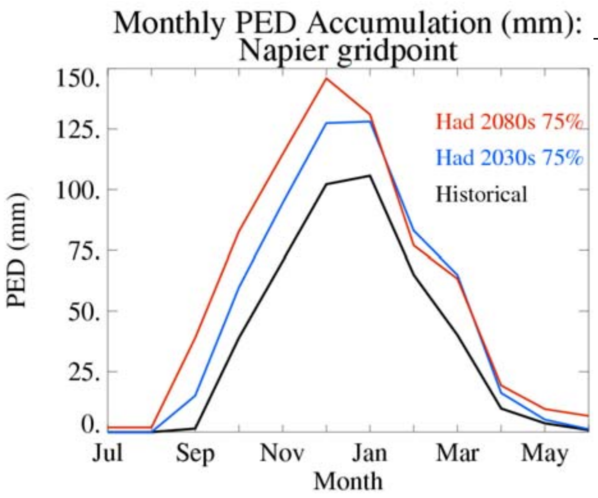


Figure 3.5 Monthly accumulation of *PED* (in mm) at the Lincoln (left) and Napier (right) gridpoints, comparing historical distributions with those projected by Hadley model with IPCC 75% scaling.

Figure 3.5 indicates how the July-June *PED* accumulation is built up over the year. The greatest increments to *PED* currently occur in December and January at the two sites illustrated, and this is predicted to continue to be the case in the future. However, under future warming there is increased accumulation throughout the year, and we can therefore infer that drought periods will tend to 'expand' into the spring and autumn months more often than currently. The average drying tendency (*PED* increment) during the spring and early summer will tend to occur about one month earlier by the 2080s under the Hadley 75% scenario (ie, the current 'dryness' at the end of November would in future occur at the end of October under this scenario).

4. Other Issues

4.1 Assumptions and Limitations

A number of assumptions and simplifications had to be made in the analysis presented in this report.

- Future changes in potential evapotranspiration (*PET*) have been estimated from historical regression relationships involving temperature, wind, and precipitation. The use of precipitation as a proxy for solar radiation (and possibly also for humidity influences) is not ideal, but necessitated by what global climate model data were available.

- In calculating future *PET*, we have assumed that carbon dioxide increase has no net effect: that is, increases in stomatal resistance (reducing transpiration) more or less compensate for increasing leaf area in terms of the effect on evapotranspiration. This assumption is consistent with the best information available to date, but because the CO_2 effect has a large potential impact on drought, we have carried out additional sensitivity tests (discussed in appendix section 6.11)

- The water balance calculation used to derive potential evapotranspiration deficit (*PED*) is straightforward, but also involves a number of assumptions about soil depth and pasture response to water stress. Different formulae have been used in the literature. Nevertheless, we have used what we consider to be the most appropriate assumptions for New Zealand pastoral regions. Section 6.4 in the technical appendix demonstrates that while the absolute *PED* level is quite sensitive to assumed soil depth, the *change* in *PED* and return periods is fairly robust.

- The future scenarios are driven by what changes the global models project for the New Zealand region, and these can vary considerably from model to model. This report has tried to cover a reasonable range of possibilities by considering two models with differing patterns of local rainfall and temperature change, and two scalings of global temperature change. As expected from its large rainfall decreases in eastern NZ, the Hadley model shows the more extreme drying. The CSIRO model also suggests a similar but weaker tendency in spite of small rainfall increases in the east over the annual cycle. The agreement in *PED* tendency between models is likely a result of the CSIRO model having a weak gradient (wetter in the west and drier in the east) in rainfall change over the critical summer months when *PET* is highest. This agreement in seasonality at a critical time of year could be fortuitous, so we cannot rule out the possibility that other models might project more benign conditions in the 2080s than this report suggests.

- The New Zealand climate change scenarios used in this report span the central portion but not the full range of IPCC projections of possible global temperature changes (1.4 to 5.8°C by 2100). Thus changes in drought risk which are smaller than those projected under our “low-medium” scenario are possible, particularly if substantial international action is taken to reduce greenhouse gas emissions. Similarly, changes greater than our “medium-high” scenario are also possible.

- Estimates of future *PED* are derived by applying offsets to the current climatology. Only changes in means of the underlying climate elements have been considered. The calculations still lead to changes in extremes (ie, droughts), but the results could be modified by future changes in daily and interannual variability, which we have not considered since climate models at present do not provide consistent projections for changes in variability.

- The projected changes in *PED* are relative to an historical baseline (1972-2003), a period probably somewhat drier in the east than for the 20th century overall because of natural decadal variations in the climate (appendix, section 6.7). Long-period natural variations will continue to influence drought risk from decade to decade, in addition to the changes expected from increased greenhouse gases.

- The *PED* calculations, and comments on drought frequency, are for unirrigated pasture. Irrigation can in principle offset increases in drought risk where sufficient water for irrigation is available. The parameters underlying the *PET* calculations are also specific to pasture. Change maps are shown for the whole country, and obviously a lot of it is not in pasture. However, we believe the changes we calculate would give at least qualitative guidance for land not currently in pasture, such as forests.

- This report focuses on drought risk, and does not explore possible implications of climate change for heavy rainfall and flooding. The report indicates that many parts of New Zealand are likely to become drier on average, but this is in terms of the moisture availability for pasture growth. It does not necessarily mean the frequency of very heavy rainfall events and floods will decrease. Other work (Wratt *et al.*, 2003) suggests the frequency of very heavy rainfall events may in fact increase in many parts of New Zealand, even in those areas where the annual rainfall decreases on average.

4.2 Issues for Further Research

Further research could assist in either reducing the uncertainty of projections made in this study, or in assessing the implications of climate change more generally on New Zealand water resources.

- Only two model patterns of local climate change were considered in this study. Obviously, increasing the number of scenarios would give a better indication of the range of possible future changes. A number of international modelling institutions plan to make their latest simulations publicly available as part of the IPCC Fourth Assessment, including experiments specifically targeting low and high emissions pathways, as well as stabilization of CO_2-equivalent concentrations at various levels. However, we do not expect the uncertainty range for New Zealand drought estimates to be substantially reduced in the near future.

- High resolution regional modelling of New Zealand climate change, currently under development by NIWA, would be preferable to relying on statistical downscaling of rainfall and potential evapotranspiration. This may provide better insights to potential changes in weather patterns and local climate changes for New Zealand, but it would not reduce uncertainties due to differences in global temperature change and broad regional climate change patterns as projected by different global climate models.

- A better understanding of the CO_2 fertilisation effect on evapotranspiration is crucial to reducing uncertainty about future drought frequency. However, the contradictory effects of increasing stomatal resistance (which decreases water loss) versus increasing leaf area and plant cover (which increases overall evapotranspiration) have been known about for some time, and a resolution does not appear to be near. Some attention should perhaps be focussed on grass species with inherently more efficient water use.

- In order to evaluate other consequences for water resources, future projections of river flow and water availability for irrigation should be considered to complement the current study on soil moisture.

- Future changes in climate variability are also possible, both natural and anthropogenic. Studies of changes in daily temperature and rainfall variability would lead to a better understanding of future water variability.

5. References

Coulter, J.D. (1973). A water balance assessment of New Zealand rainfall. *New Zealand Journal of Hydrology, 12:* 83-91.

IPCC, (2001). *Climate change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. JT Houghton, Y Ding, DJ Griggs, et al (eds). Cambridge and New York: Cambridge University Press.

Mullan, A.B.; Wratt, D.S.; Renwick, J.A. (2001). Transient model scenarios of climate changes for New Zealand. *Weather and Climate, 21:* 3-33.

Porteous, A.S.; Basher, R.E.; Salinger, M.J. (1994). Calibration and performance of a single-layer soil water balance model for pasture sites. *New Zealand Journal of Agricultural Research, 37:* 107-118.

Porteous, A. (2004). Changes in drought risk with climate change. Part 1: Defining a climate change sensitive drought index. NIWA Client Report WLG2004-49 prepared for New Zealand Ministry for the Environment, June 2004, 39p.

Tait, A.; Henderson, R.; Turner, R.; Zheng, X. (2005). Spatial interpolation of daily rainfall for New Zealand. *International Journal of Climatology*, (in preparation).

Wigley, T.M.L.; Raper, S.C.B. (2001). Interpretation of high projections for global-mean warming. *Science*, 293: 451-454.

Wratt, D.; Mullan, B.; Salinger, J.; Allan, S.; Morgan, T.; Kenny, G. (2003). Overview of Climate Change Effects and Impacts Assessments – A guidance manual for local government in New Zealand. NIWA Client Report WLG2003/44, prepared for Climate Change Office, Ministry for the Environment, 141p. (available from website: http://www.climatechange.govt.nz/resources/local-govt/effects-impacts-may04/index.html

6. Technical Appendix

6.1 Drought Indicator Issues: Notes from Expert Workshop

6.1.1 Drought risk workshop

The key objective of the workshop was to propose a quantitative indicator that could be used to assess potential changes in drought incidence and severity with climate change. This required a consultative process to draw from previous New Zealand experience using drought assessment indicators, and their potential suitability for this objective.

To this end NIWA and the Ministry for the Environment hosted a drought risk workshop at Greta Point, on 10 May 2004. The workshop brought together scientists and consultants from NIWA, Ministry for the Environment, AgResearch, Crop and Food, Earthwise Consulting, Fonterra, MAF Policy, and Wrightson Consulting.

The workshop reviewed aspects of how past droughts in New Zealand had been measured and assessed, and identified many issues which needed to be considered in arriving at a 'most suitable' drought index. These issues are noted in the following section.

6.1.2 Identification of key issues

The main purpose of the drought index was to compare the risk now with the risk in say 50 years' time, eg. 'There will be 30% more droughts then than now'. The index might describe both relative and/or absolute change. Participants noted that it was also likely to have implications for future water use allocation, for example rural versus urban water quotas, and water abstraction. It might help with quantifying flow-on economic impacts from potential changes in agricultural production. The drought index might also indicate further research needs, particularly in issues like ground water abstraction, irrigation scheduling, and social costs.

In Canterbury at present, water allocations are made on the basis of rainfall volumes, as not enough is known about flow-through volumes in rivers and groundwater. It is possible that water in Canterbury is already over-allocated.

The workshop recognised that drought usually has the largest impacts of any national or international calamity on the economy of New Zealand. For example, the drought of 1997-98 was bigger economically for New Zealand than the 'Asian crisis' (although currency fluctuations also had an impact). Heavy reliance on rain-fed agriculture meant that just 21 days without rain was often enough to trigger drought like conditions.

Concern was expressed that any drought index identified for the current purpose should not be used to 're-litigate' recent drought conditions, or be applied to such purposes as redistribution of current water rights.

Although not relevant to the present aim to derive a drought risk indicator, it is relevant to quantifying the economic impacts of climate change to note that droughts are always disadvantageous for some, but are often advantageous for others. Hence economic measurements of drought must recognise that impacts are not contained within affected regions; there may be positive impacts elsewhere. For example, stock moved from a dry region may benefit farmers in higher rainfall areas; trucking companies who move the stock gain extra income.

Over the past few years farmers have adapted well to short (eg. 3-month) droughts, but prolonged droughts have more profound impacts. Of particular concern is when severe droughts lead to disposal of capital stock or specialist breeding stock. It is important to establish benchmarks or trigger points for making critical decisions. It may also be important to have an indication of recovery time – eg. the amount of rainfall required to bring the drought to an end.

A drought index is no use in isolation – it must be capable of measuring something else, for example, production. Different indices may be needed for example for different cropping systems, or to adequately represent hydrological conditions. The timing of drought is therefore important. A late season drought, after harvest, may not be important to cropping farmers. Much more data are available now, and holistic interpretations of drought need to be considered. On the other hand, pastoral, rain-fed agriculture will be dominant for a long time in terms of the national economy. However it may be important to distinguish between dry land and irrigated agriculture. It may be possible to access a water consent database to obtain location, volume, and land use. This would also provide information in water restrictions. A further possibility would be to attach land use properties to indicator climate stations (water use, farm type, catchment area).

Drought risk changes are not just meteorological – risk can also change because of socio-economic and technological changes. An ideal index would be derived from a biophysical model, but with strong linkages to social and economic outcomes.

Extreme droughts can trigger species and ecosystem changes, for example, a change from C3 to C4 grass species.

There are some advantages of having an index that is independent of land use. In this case a range of 'what-if' scenarios could be used to account indirectly for land use. Some examples would be varying soil types and root depths, key return period thresholds, and proportion of irrigated versus non-irrigated land. An extension of an irrigation usage scenario could be various water abstraction rates. It is important also to account for situations where the source of water can be different to its place of use. For example, one estimate suggests 70% of Canterbury's water resource is from rainfall in the Southern Alps.

A drought index should clearly show the impact on pasture growth[1]. However pasture growth is heavily dependent on solar radiation, and changes in radiation (and cloudiness) with climate change are highly speculative at this stage. Climate change scenarios in this study are based on changes in rainfall, air temperature, and circulation

[1] It was noted that AgResearch with Crop and Food have developed a pasture growth model, which could be applied to drought scenario studies.

regimes. However, estimates of variability in radiation and windiness from historical data, particularly their link to changes in observed drought incidence, would be useful to test the sensitivity of future drought risk to similar variability within climate change scenarios. The level of uncertainty associated with changes in radiation (and also with the degree of change in windiness) is a component of the uncertainty in changes in drought risk resulting from climate change.

A starting point could be a model of unrestricted (by lack of moisture) pasture growth, and then modify the outcome with increasing deficit. A refinement would be to model species change that may occur as a result of climate change.

The workshop recognized the potential importance of information on changes in drought risk within boundaries of district and regional councils, to improve information for local authority decision-making.

Finally, from a science perspective, it is easy to define an index. It is however harder to ensure that it is the most suitable index for the intended purpose. The limitations of a proposed index should be clear, as also possible ways it might be improved.

6.1.3 Desirable properties of a drought index

- Universality – the index should be applicable to all parts of the country, and be suitable for both nation-wide and regional analyses. The index should also be sufficiently versatile to cope with varying thresholds or scales of severity.
- Easily interpreted
- Supported by readily available data to enable calculation of robust anomaly and recurrence statistics
- Should enable improved advice to farmers for land use planning
- Be an indication of production loss.
- Be suitable for subsequent research needs – eg. land use, social implications, water policy.
- Be based on parameters for which predictions of future change can be plausibly developed, given current knowledge.
- Be able to be linked to decision trigger points (eg. the kinds of thresholds that farmers might use to implement drought mitigation actions).
- Represent both the duration and intensity of droughts, as both are important.

6.2 Literature Review of Drought Indicators

This section outlines examples of drought indicators from the New Zealand and international experience. These examples provide a broad context against which the relationship between climate parameters and drought risk can be established. Of key interest are the features of drought indicators that most clearly define differences between drought events, particularly where they are relevant to the requirements of this study.

Drought indicators are inherently complex due to the multiple causes, processes and impacts of drought. The difficulty of obtaining relevant data series, and, more importantly, of modelling the interactions between natural processes and human responses, typically leads to drought assessments being oversimplified. In this section, some examples of drought indicators from New Zealand, Australia and the United States are given, as a background to the selection of an appropriate drought index for New Zealand.

6.2.1 New Zealand

In New Zealand, up to about the late 1980s, drought relief consideration for farmers was triggered when rainfall at representative climate stations in a drought-affected area, for a consecutive three-month period, was at a one in 20 year low. This measure was often further qualified by the additional condition that total days of soil moisture deficit, based on a daily water balance calculation, were correspondingly high.

Economic consequences of drought have been reported in various ways, including:

- Loss of gross farm income (individual and regional);
- Loss of production (various categories);
- Changes in expenditure patterns including wages;
- Loss of value added including feed stocks;
- Run down in savings;
- Changes in stock numbers;
- GDP losses. For example, the New Zealand Institute of Economic Research estimated that the 1997/98 El Niño associated drought resulted in a loss of $407 million (0.4%) of GDP (Gardiner 2001).
- Environmental consequences.

6.2.2 Australia

Following the severe eastern Australian drought of 1994/95, the Australian Government adopted a policy of Drought Exceptional Circumstances for intervention (Laughlin and Clark, 2000), based on the assessment of six criteria:

1. Meteorological conditions;
2. Agronomic and stock conditions;
3. Water supplies;
4. Environmental impacts;
5. Farm income levels;
6. Spatial scale of the event.

The Criteria for Exceptional Circumstances are that:

1. The event must be both *rare* and *severe*. A rare event is one that occurs once in every 20-25 years. A rare event is severe if it is of a significant scale – measured by the number of farm businesses affected, sector impacts, size of the area affected, and overall value of lost production.

2. The effects of the event must result in a severe downturn in farm income over a prolonged period.

3. The event must not be predictable or manageable through normal risk management strategies available to farmers, or be part of a process of structural adjustment.

For example, the drought of 2002-2003 had significant impacts (Adams *et al*., 2002):

- 30% reduction in 2002-2003 agricultural output, equivalent to 1% of GDP
- Flow-on effects to rest of economy lowered 2002-2003 GDP a further 0.6%
- Net effect on 2002-2003 GDP was a loss of 1.6%
- Loss of 70,000 jobs, mainly in wholesale, retailing and repairs (25,000), transport (9,000), business services (12,000), agricultural services (5,500, e.g. crop spraying and harvesting) and food processing and beverages (10,000).
- Worst affected regions, in terms of Gross Regional Product, were south-west Queensland (-21%), north-west NSW (-18%), the Victorian Mallee (-16%) and northern NSW (-15%)

6.2.3 United States

Byun and Wilhite (1999) argued that most currently used drought indexes were not precise enough to detect the onset, end, and accumulated stress of drought.

They suggested four classes for the study of drought:

1. Causes – directed at understanding atmospheric processes that lead to drought;

2. Frequency and severity – directed at characterizing the probability of drought events of various magnitudes;

3. Impacts – directed at quantifying the costs and losses associated with drought, including economic, social and environmental consequences, which may be direct or indirect;

4. Responses – directed at preparedness and mitigation strategies, and focusing on means of impact reduction.

These writers noted that most drought indices were based on meteorological or hydrological variables only. They pointed out a number of aspects of these indices which could be improved, highlighting the following features:

1. **Accumulated deficit.** Drought indices should be calculated with the concept of consecutive occurrences of water deficiency, rather than just the departure from climatological mean for a predefined period, as was currently the case.

2. **Time step.** Daily units of time were essential, because a water deficit could be overcome by just a day's rainfall. Most indices were based on monthly time steps.

3. **Water storage term**. Drought indices should characterise both soil moisture and other water resource (eg. lakes, ground water) storage as separate features. Byun and Wilhite noted that the Palmer Drought Severity Index (Palmer 1965), and the Surface Water Supply Index (Shafer and Desman 1982) considered these two features separately; others did not.

4. **Time dependent reduction function.** This was needed to account for daily water resource depletion through runoff, evapotranspiration and other factors, particularly to evaluate the residual resource of rainfall that had occurred some months previously.

5. **Problems with modelled or estimated data.** Oversimplification of data, for example soil moisture content, was inevitable because of variability in topography and other soil characteristics. It was better to use measured parameters only, such as precipitation.

6. **Lack of other information.** Drought indices failed to provide good information on the duration of drought, how much deficit of water had occurred, when the drought was likely to end, and how much rainfall was needed to return to normal conditions.

The writers introduced a new concept, effective precipitation (EP). Total precipitation over a period, for example a year, defined the water resource, and the contribution to the resource of each rainfall event (the EP) was qualified by how long ago it occurred (i.e. its input value decayed over time). Drought duration was then calculated from the number of consecutive days when EP was less than a derived normal, and drought severity was taken to be the depth of the accumulated deficit. A further term, the precipitation needed for a return to normal, was also calculated. Finally the writers proposed a number of drought severity indices that could be derived using this procedure.

National Drought Mitigation Centre

The Western Drought Coordination Council (1998), supported by the National Drought Mitigation Centre, University of Nebraska-Lincoln, describe the need for environmental, economic and social information to define drought and its impacts. They add that local customisation of drought information is essential because the causes and impacts of drought vary regionally. They argue therefore that the scale of the information should be:

> 'representative of the area experiencing drought and comprehensive enough to adequately examine corresponding impacts'.

The points noted below are included in their recommendations for drought indicator information.

i) Environmental information

- Precipitation – indicates which regions are most susceptible to drought, and characterises drought patterns over time in drought prone areas;

- Water supply sources – both surface and ground water, including managed (dams) and unmanaged. It's important to know when water sources are located in a different hydrological basin to where a drought occurs;

- Impacts of soil loss and sediment deposition – an example would be sheet erosion due to heavy rain following dry periods;

- Impacts on surface and ground water, from soil moisture to lakes and wetlands, including both quantity and quality of water;

- Effects on air – for example dust storms;

- Effects on wild life and plants – impact on habitats, diversity, and stress on species;

- The connection between drought and wild fires – both forest and rangeland, following extended dry periods, including both immediate and residual impacts.

ii) Economic information

- Understanding economic linkages and trends. While the impacts of drought may be felt first in the agricultural sector, there are always flow-on effects in many other sectors of the economy. In addition, the impact on rural communities and on families is often severe.

- Other economic factors – eg. awareness programmes, drought recovery loan schemes, and insurance.

iii) Social information

- Public health and safety – there are many issues here including health risks due to water shortages or contamination in dry seasons, mental and physical stress brought on by the situation, and the physical dangers posed by fires.

- Individuals' perceptions of drought – differing 'interpretations of drought characteristics may produce different attitudes and perceptions of how to deal with drought'.

- Acknowledging diversity – there is a wide range in the way drought affects people, because of diversity in social, cultural and economic circumstances.

- Government/NGO interactions – dialogue is important to determine best policy implementations for drought preparedness and relief.

- Political or government perspectives – avoidance of conflicting objectives in the management of economic sectors, where they make effective drought planning more difficult.

iv) Customized information

It is important that drought assessments and declarations are appropriate and accurate to the localities that are affected. Regional assessments of drought may be too general.

U.S. Department of Agriculture

The United States Department of Agriculture, in its report to the National Drought Policy Commission, highlighted the use by various agencies of 'trigger points' for drought assessment (USDA 2000):

> '… public declarations of drought are often triggered by specific and well-defined conditions, such as a specific reservoir elevation on a specific date. In some cases, there are well-defined exit points that trigger a resumption of normal activity. These "drought triggers" become the practical definition of drought for a particular region and for specific issues. Defining these triggers is an inseparable part of planning for and responding to droughts. Once these

> triggers are defined, a region is much better able to estimate the costs, expected frequency, and risks of drought response.'

The Commission report further recommended that drought triggers should be both *supply-type*, reflecting moisture deficiencies caused by acts of nature (lack of rain, excessive temperatures), as well as *demand-type*, reflecting drought impacts.

Examples of current supply-type triggers used in general to define drought or trigger actions related to potential drought included:

- Precipitation less than 60% of normal for the season or present water year (used by the National Weather Service's Western Region);

- Precipitation less than 85% of normal over the past six months (used by the National Weather Service's Eastern Region);

- The Palmer Drought Index -2.0 or less;

- Consolidated drought indices at the 20th percentile or less (used by the Drought Monitor). For Federal action, more rigid triggers such as the 5th percentile drought might be appropriate, reflecting truly unusual circumstances.

Examples of demand (impact) based triggers included water supply less than 60% of normal (used by the National Weather Service's Western Region) and various crop loss thresholds, used by the U.S. Department of Agriculture.

6.3 Calculation of Potential Evapotranspiration Deficit

The water balance calculation used to derive the Potential Evapotranspiration Deficit (*PED*) drought index assumes that the water gains and losses to the soil profile are typically in balance. Provided water is non-limiting the balance for a given rainfall period can be written:

$$P = PET + Ro + D \pm \Delta S$$

Where P is precipitation, PET is potential (or upper limit) evapotranspiration, Ro is surface runoff, D is drainage loss through percolation, and ΔS is the change in water storage. For the purposes of this study, PET is calibrated for pasture water use.

In principle, for each day,

$$S = S_{d-1} + P - PET - Ro - D$$

where S is the new storage, and S_{d-1} is the water storage for the previous day.

Field capacity water storage is defined by the available water capacity *(AWC)*, which we have taken to be 150 mm for this study. Rainfall in excess of field capacity is assumed to be lost to the water balance by runoff and drainage.

if $S_{d-1} + P - PET > AWC$
then $(S_{d-1} + P - PET) - AWC = (Ro + D)$

As S is reduced, it becomes increasingly difficult for plants to extract water from the soil, and water transpiration decreases. Here we have used a method of estimating constrained water use by assuming evapotranspiration (ET) continues at its potential rate until half *AWC* is depleted, following which it ceases until further rain occurs.

if $S < \frac{1}{2}(AWC)$
then $ET = 0$

The difference between the subsequent soil water-restricted evapotranspiration, *(RET),* and the atmospheric potential evapotranspiration for the period *(PET)*, is referred to here as the potential evapotranspiration deficit *(PED)* and is incremented on a daily basis.

$$PED = PED_{d-1} + (PET - RET)$$

In effect, *PED* is approximately equivalent to the amount of water that would need to be added by rainfall or irrigation to keep pasture growing at its daily potential rate.

PED was accumulated daily for the July to June year, beginning from zero each year. Note that the soil moisture deficit carries over from one year to the next, even though *PED* is reset at the beginning of each July-June period. The water balance calculation was initiated on 1 January 1972, so there was a potentially non-zero starting value of soil moisture deficit at the beginning of July 1972.

PED is closely related to the frequently used 'Days of evapotranspiration deficit', which are days on which pasture is growing at less than its potential rate for a given season.

Figure 6.3.1 below shows the relationship between the potential evapotranspiration deficit and the number of days of deficit for Lincoln, for July to June seasons from 1881/82 to 2003/04. The data show that the average annual *PED* at Lincoln is about 400 mm, which equates to about 100 days of deficit.

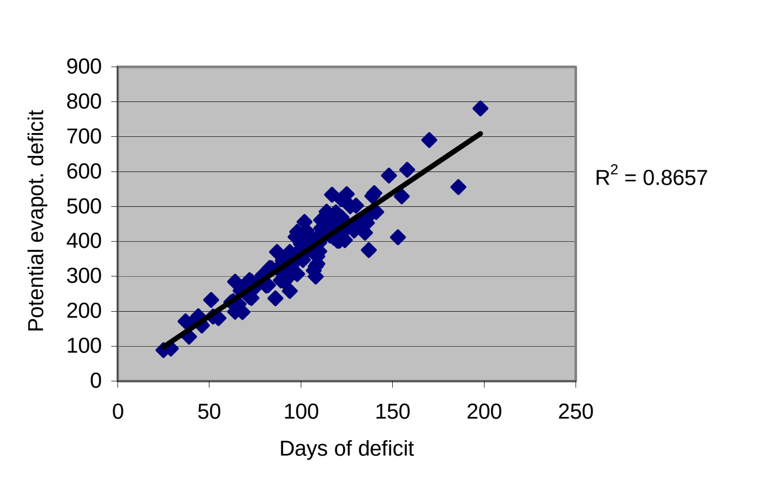


Figure 6.3.1 Relation between the potential evapotranspiration deficit (in mm) and the number of days on which an evapotranspiration deficit occurred, calculated with the method shown in Appendix (section 6.3), for Lincoln, July to June seasons from 1881/82 to 2003/04.

6.4 Sensitivity of Potential Evapotranspiration Deficit to Rainfall and Available Water Capacity

As described in Section 3, in this study we have applied a range of projected rainfall offsets to the current climate to estimate changes in *PED* under future climate. Only changes in means of the underlying climate elements have been considered. Changes in modes of rainfall, such as the number of wet days per months or the daily persistence of rainfall events, were not considered.

Historical data show that there is a reasonably strong relationship between inter-annual variation in rainfall and changes in *PED.* Figure 6.4.1 illustrates the dependence of *PED* (based on an Available Water Capacity of 150mm, half of which is 'readily available' in the root zone) on rainfall during the height of the growing season (November through April), using the observed relationship at Napier for 1941-2004. The data suggest an approximately 80 mm increase in *PED* is likely for each reduction in rainfall by 100 mm. The data also illustrate how equivalent *percentage* reductions in rainfall in wet seasons have more impact on *PED* than in dry seasons. For example, from the equation, a 10% reduction in seasonal rainfall from 600 mm to 540 mm lifts *PED* from 196 mm to 244 mm, or 48 mm, while a 10% reduction from 200 mm to 180 mm of rain increases *PED* from 516 to 532 mm, or just 16 mm.

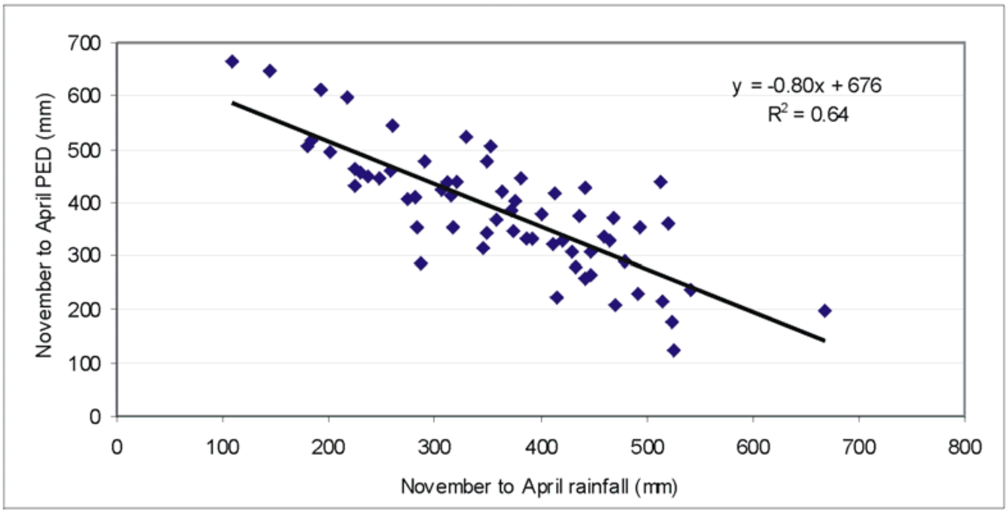


Figure 6.4.1 Dependence of November to April *PED* on rainfall for the same period, at Napier (Nelson Park site).

In a similar way, we might expect that shallow soils, where *PED* is already typically high under the present climate, are likely to be less impacted under climate change, relative to current *PED* levels, than deep soils with currently low *PED*. This is illustrated in Table 6.4.1.

Table 6.4.1 ***PED*** **characteristics for 5 available water capacities, at Napier (Nelson Park). Results are shown for the current climate and for a perturbed climate with a 10% daily rainfall reduction.**

Available water capacity (mm)	Mean PED, current climate (mm)	PED range, current climate	1-in-20 year PED current climate	Mean PED with 10% rainfall reduction	Change in mean with rainfall reduction	Perturbed PED range	1-in-20 year PED, perturbed climate	New average recurrence interval (years)
70	482	209-737	699	505	23	244-758	720	14.8
100	447	162-722	681	473	26	186-743	703	14.7
150	406	116-697	658	435	29	146-718	679	14.8
220	365	81-662	625	397	32	111-583	646	14.9
310	321	36-617	583	358	37	66-638	611	13.2

Table 6.4.1 shows example water balance output for an idealised 10% reduction to all rainfalls for the years 1949 to 2004. Other meteorological conditions were assumed to remain constant. The water balance was run for five available water capacities as shown. Return periods were calculated using the same algorithm as in the main report (Kim *et al.,* 2003). A 1-in-20 year *PED* for each available water capacity under the present climate (fourth column) would recur (given a 10% rainfall reduction) on average at intervals shown respectively in the final column. For example, a 1-in-20 year *PED* for an available water capacity of 150 mm would become a 1-in-15 year drought after a 10% rainfall reduction.

Throughout this report (apart from Table 6.4.1), all *PED* calculations are done using a uniform 150mm Available Water Capacity across the country, which is considered reasonably typical. One feature that Table 6.4.1 highlights is that return period changes are surprisingly robust across a range of water capacities. This suggests that our return period calculations are applicable to a range of soil depths.

6.5 Downscaling Potential Evapotranspiration

Potential evapotranspiration has been calculated in many different ways – see McKenney and Rosenberg (1993) for a review of eight alternative estimation methods. The fundamental climate elements involved are solar radiation, temperature, humidity and wind speed. Section 6.5.1 discusses factors influencing evapotranspiration, and notes observational relationships.

Unfortunately, the climate elements most readily available from climate models (precipitation, temperature and mean sea-level pressure) do not match the list above. The approach we have therefore taken in this study is to estimate *PET* variations from the available climate model data instead. Two steps are required before future scenarios of *PET* can be generated. Firstly, it is necessary to check the validity of replacing the 'primary' climate elements (radiation, temperature, humidity and wind speed) by those available from the models. This exploratory analysis is carried out on station data (section 6.5.2). Secondly, a downscaling procedure is needed to convert the changes at the global model grid-scale to *PET* changes on the 0.05° grid (section 6.5.3).

6.5.1 Sensitivity of *PET* to changes in climate

Air Temperature

Air temperature influences evapotranspiration in several ways, principally by determining the maximum amount of moisture the air can hold, and by the amount of energy that is supplied to evaporating surfaces. Higher temperatures typically increase the evapotranspiration potential, and thus the potential for increased drought risk.

Figure 6.5.1 shows the relationship between mean temperature and potential evapotranspiration (*PET*) at Christchurch Airport. Although the explained variance in *PET* is low (~30%), there is a clear trend of higher moisture demand in years with higher temperature. The highest *PET* (1001 mm) occurred in the warmest year, the La Niña season of 1988-89.

The data in Figure 6.5.1 suggest that a 2°C increase in temperature may raise *PET* by about 10%. However, preliminary work elsewhere on the relationship between mean air temperature and *PET* has indicated increases in *PET* of about 5% with a 2°C temperature rise (e.g. McKenney and Rosenburg, 1993). The data presented in Figure 6.5.1 show that relatively high (in comparison to temperature) *PET* occurred in several of the El Niño years, particularly the events of 1997-98 (marked 1 in the figure), 1991-92 (4), 1982-83 (3), and 1977-78 (2). Given the typically windy nature of El Niño events in Canterbury, *PET* increases in these years are likely to have been at least partly attributable to increased windiness.

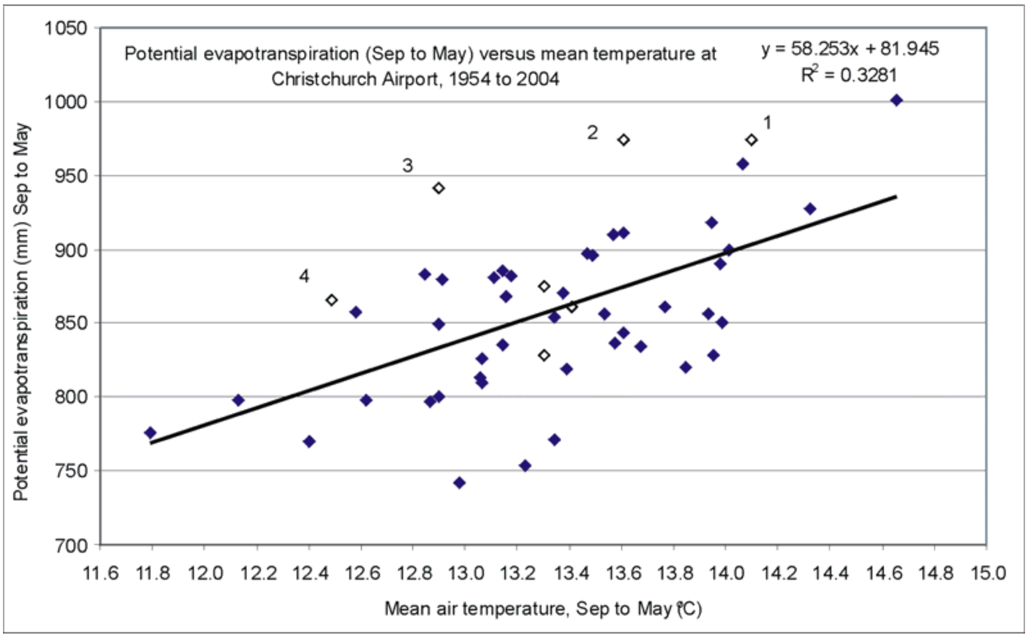


Figure 6.5.1 Apparent relationship between seasonal (September to May) mean air temperature and calculated potential evapotranspiration (*PET*) at Christchurch Airport, 1954-55 to 2003-04. The highest *PET* (1001 mm) occurred in warmest year, the La Niña season of 1988-89. Open points are El Niño years; enumerated points are referred to in the text. The trendline is indicative only.

The relationship between temperature and potential evapotranspiration raises the possibility that the higher temperatures expected with climate change may in any case increase the risk of drought, even if rainfall does not decrease.

Wind

Wind typically plays an important role in evapotranspiration, by increasing turbulence and facilitating the movement of moisture-laden air into the drier atmosphere. Wind increases the loss of moisture from wet surfaces, but where there is no moisture, for example in a very dry paddock, little additional loss of moisture may occur. Therefore, if windiness increases with climate change, it is likely to increase moisture loss while moisture is still available (for example early in the growing season), and thus potentially hasten the onset of drought.

As noted above, changes in windiness associated with El Niño seasons may partly explain increases in evapotranspiration during those seasons, though further work is needed to separate this effect from the influence of air temperature on its own. McKenney and Rosenberg (1993) obtained a similar trend in their work at two relatively windy North American sites, where they found that a 20% increase in wind speed led to a 9% increase in *PET*.

Solar Radiation

Solar radiation is the main source of energy for evapotranspiration. Solar radiation incidence is likely to change if cloudiness changes with climate change. For this study an estimate has been made from historical data of the variability of incident radiation using rainfall as a proxy indicator. The estimates show that evapotranspiration is inversely dependent on cloudiness, and this has been taken into account in calculating changes in *PED* with climate change.

6.5.2 Use of proxy variables to describe *PET* variations

Many changes in climate elements are interrelated. For example, a very sunny month (anomalously high solar radiation) at some location is also likely to be a dry month (anomalously low rainfall). Thus, it seems reasonable to try using precipitation as a proxy for solar radiation in a regression equation for *PET*. Local wind variation is notoriously difficult to predict, particularly in New Zealand's variable terrain. On the larger scale, though, wind is related theoretically to pressure gradients, so the use of some pressure index suggests itself as a proxy for site-specific windrun.

Figure 6.5.2 shows results from attempts to predict interannual variations in *PET* at a number of climate sites using multiple linear regression. The length of record is variable: Napier (1950-2003), Masterton (1950-1991), Blenheim (1953-1987), Lincoln (1950-1987), and Dunedin (1991-1999). The record length is selected to avoid any site changes that could adversely affect the homogeneity of the data. Separate regression equations are estimated for each calendar month.

For the first five panels of Figure 6.5.2, the predictors are: precipitation, temperature, and "wind". Three curves are plotted according to what wind measure was chosen: windrun at the site (which we would assume to be the most reliable), the "Z1" pressure index (anomalous pressure difference between Auckland and Christchurch), and both Z1 and "M1" (anomalous pressure difference between Hobart and Chatham Island). These pressure indices were tested because they have been widely used in New Zealand climate analysis since originally devised (Trenberth, 1976), are predictors in previous downscaling work (Mullan *et al.,* 2001), and can be readily calculated from model grid data (either historical analyses or future projections).

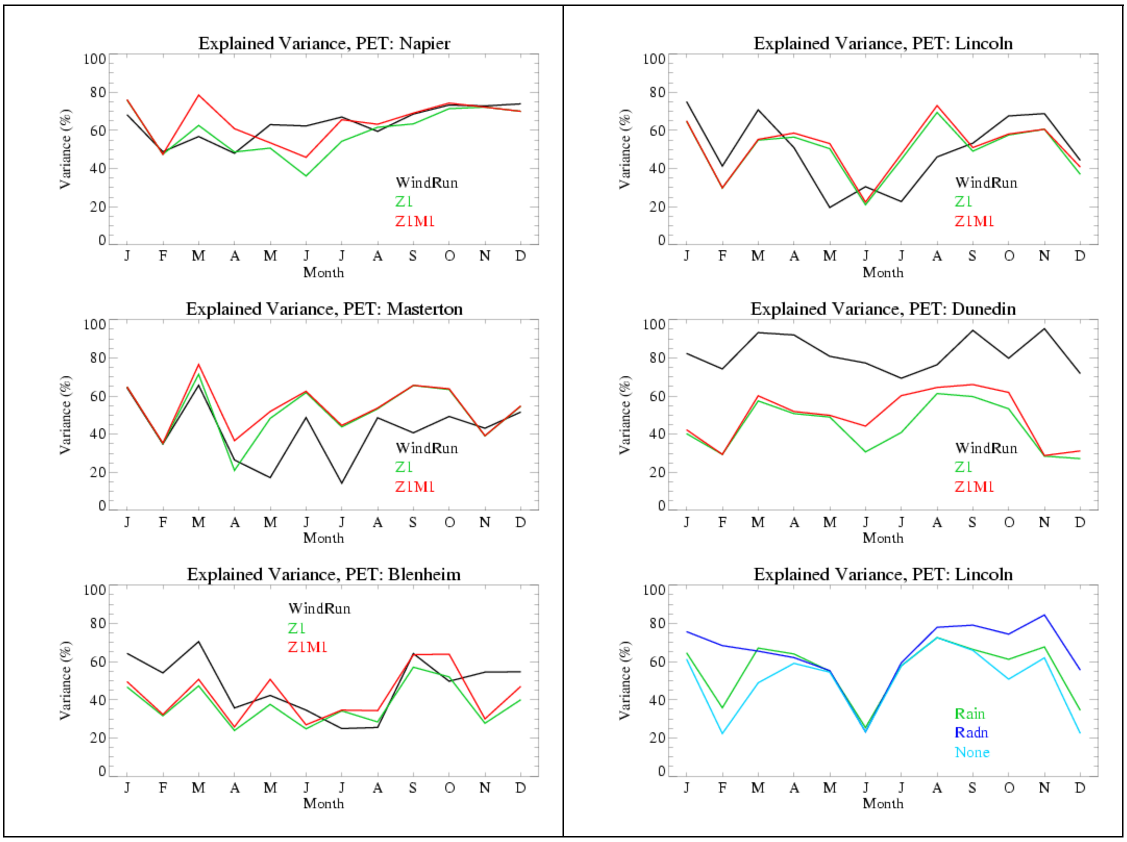


Figure 6.5.2 Explained variance (%) of monthly *PET* from multiple linear regression estimates. First five panels show effect of replacing station windrun with a pressure index. Last panel (lower right) shows effect of using rainfall as proxy for solar radiation at Lincoln.

Results show that the *PET* explained variance is maintained fairly well when site windrun is replaced by the pressure index Z1 (except for the short record site of Dunedin). There are even instances where the local evapotranspiration is better estimated using Z1 than the local wind (Masterton).

The bottom right panel of Figure 6.5.2 shows a similar intercomparison for the Lincoln site (where long-term solar radiation records are available) using predictors: temperature, windrun, and either radiation, rainfall, or neither. It is clear that it would be valuable to have solar radiation as a predictor, particularly over the summer months when *PET* is highest. However, having rainfall is better than nothing.

6.5.3 Multiple linear regression downscaling of *PET*

The *PET* on the New Zealand 0.05 grid covers the period 1972-2003. Monthly anomalies (as %) were modelled by multiple linear regression using for predictors: precipitation (%) and temperature (C) at the same gridpoint, and Z1 and M1 pressure indices calculated from NCEP-NCAR reanalysis mean sea-level pressure data. (All the predictors are anomalies from their respective monthly climatologies). Figure 6.5.3 shows the explained variance (on the dependent data) for spring and summer months, aggregated into seasons. It is particularly satisfying that the explained variance is highest (and very significant, statistically) in the eastern drought-prone regions where our estimate of *PET* is most critical. The explained variance is lowest in the winter season (not shown) when absolute levels of *PET* are very low.

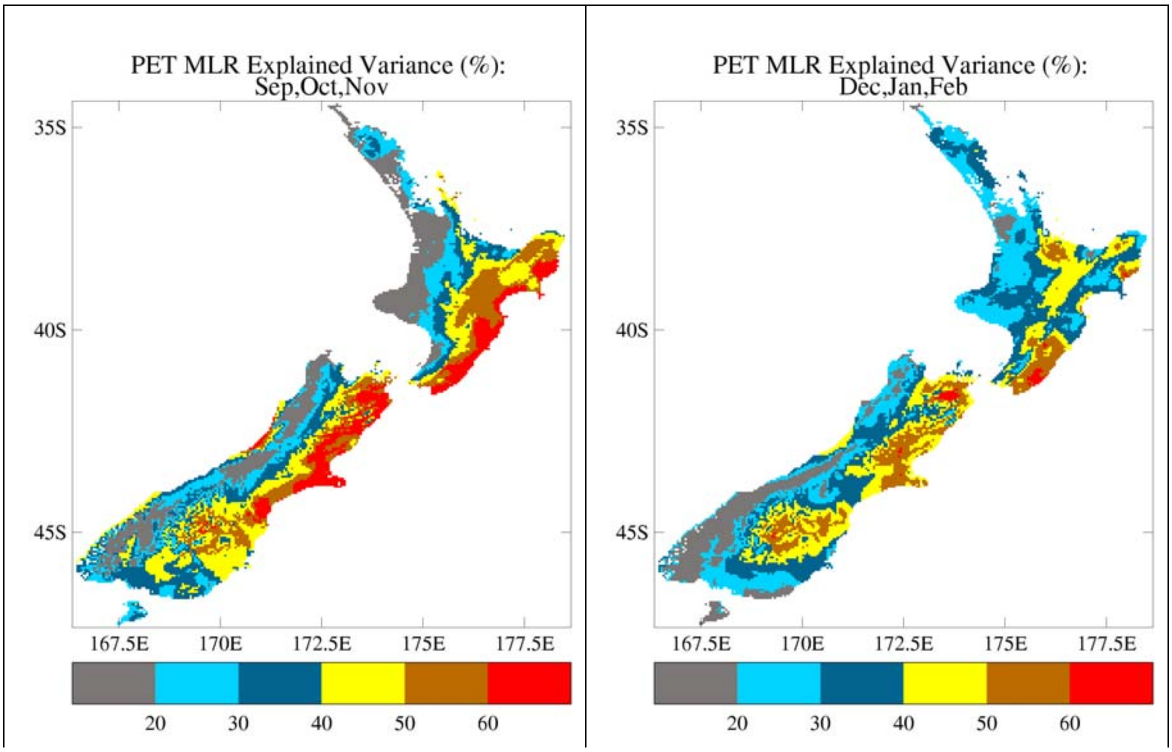


Figure 6.5.3 **Percentage of variance explained by the *PET* multiple linear regression for: the three spring months (left panel) and three summer months (right panel) combined.**

The individual predictor coefficients (maps not shown) look physically sensible. Over most of the country, the precipitation coefficient is negative (more precipitation meaning less solar radiation and therefore lower *PET*), and the temperature and Z1 coefficients positive (increased *PET* for higher temperature and stronger winds). For the drier eastern regions of New Zealand, the temperature regression coefficients suggests a range of 2-8% increase in *PET* per 1°C increase in local temperature, which is consistent with the single variable regressions noted in section 6.5.1. In eastern regions, the wind regression coefficients (not shown) suggests a 1-2% increase in *PET* per 10% increase in mean westerly wind speed, which is somewhat lower than the observational result from McKenney and Rosenberg (1993).

Future scenarios of monthly *PET* change are estimated by applying the regression equations to model projections of mean changes in the four predictors (temperature, rainfall, Z1 and M1).

6.6 IPCC 25% and 75% scaling of GCM patterns

The CSIRO Mark2 and Hadley Centre HadCM2 global climate models on which our scenarios are based were idealised transient simulations using 1% per year compounding carbon dioxide concentration. Their global average surface air temperature projections lie in the middle of the IPCC range (Figure 6.6.1, where the IPCC low/high envelope is taken from the IPCC Third Assessment, Cubasch *et al.,* 2001). Rather than use the model changes directly, they were rescaled to take some account of uncertainty in model projections and emission scenarios. See Appendix 2 of Wratt et al. (2003) for further discussion of rescaling the local climate change projections.

Mullan *et al*. (2001) downscaled climate projections for New Zealand from six global climate models. Although only two models are studied in this report, all six models are used in the rescaling procedure, which is as follows. From the global temperature changes of the six models (four only beyond 2050), we determine the scaling factor that reproduces the IPCC envelope – that is, what factor makes the 'coldest' model match the IPCC lower bound, and what factor makes the 'warmest' model match the upper bound. This was the procedure used in Wratt *et al.* (2003) to generate the extreme IPCC range for New Zealand changes, where all the model changes were multiplied by these 'lowest' and 'highest' factors to represent the full spectrum of possible changes. For example, for the 1990 to 2080s change, these extreme scaling factors are approximately 0.55 and 1.44 for the suite of available global models.

In this report, we focus on 'low-medium' and medium-high' scenarios instead of the IPCC extremes (for reasons mentioned in section 1.3). We define these scenarios as arising from factors one-quarter and three-quarters of the way between the extreme factors. These points are denoted as the IPCC 25 percentile and 75 percentile scaling factors.

The 25% and 75% scaling factors are given in Table 6.6.1. Figure 6.6.1 shows the rescaling schematically. In practice, all the temperature changes are for 30-year averages (2020-2049 and 2070-2099), not individual years. This method may seem unnecessarily complicated. However, we *cannot* scale the model projections so that the individual model global temperature matches the 25% and 75% points of the IPCC temperature range, since this could push other models outside the IPCC extreme bounds. (Such a scaling is clearly wrong at the extremes).

Table 6.6.1 Scaling factors applied to the CSIRO and Hadley projections to mimic the IPCC 25 percentile and 75 percentile in global mean temperature change.

Time Period	25%	75%
1990 to 2030s	0.68	0.96
1990 to 2080s	0.77	1.21

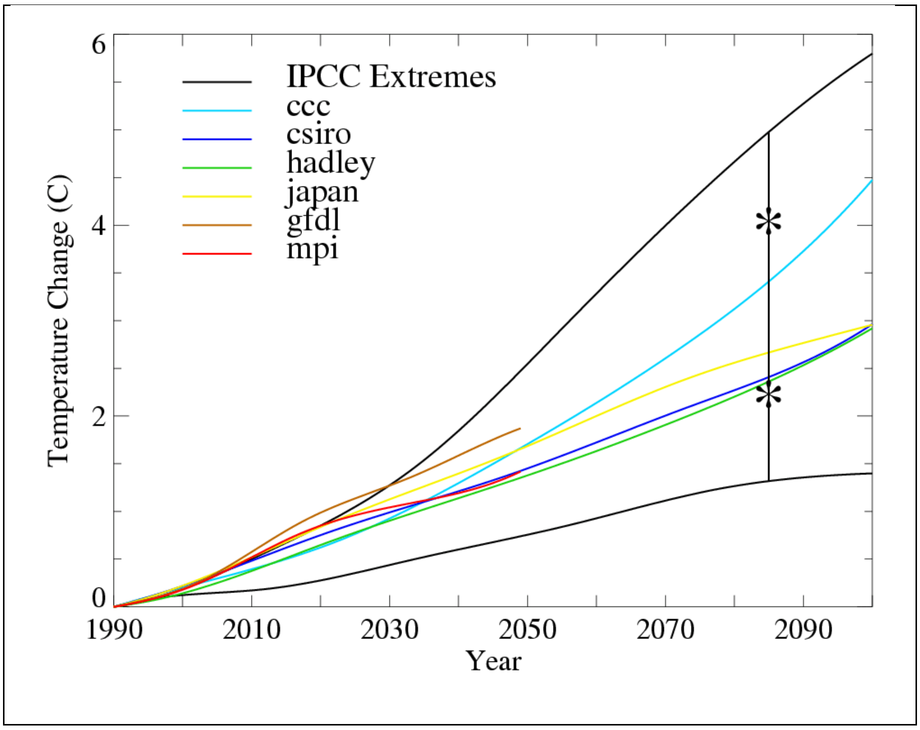


Figure 6.6.1 Global-mean surface temperature changes from a range of models (coloured lines), and the IPCC extreme range (black lines). Stars on the vertical bar at 2085 indicate *schematically* the IPCC 25 percentile and 75 percentile for the 2080s. Note that in practice (see text) we use a 30-year period, not a single year, and calculate the quartiles of the extreme low to high scaling factor range, not quartiles of the temperature change.

For the CSIRO and Hadley models, the scaled global-average temperature increase by the 2080s lies between 1.8°C (the 25% scaling) and 2.9°C (the 75% scaling). For the year 2100, this would correspond to a range from about 2.3°C to 3.6°C. This is slightly below the quartiles of the widely quoted 1.4°C to 5.8°C IPCC range at 2100 (i.e., 2.5°C and 4.7°C) because the CSIRO and Hadley models have a lower global climate sensitivity than some of the other models used in the IPCC Third Assessment.

6.7 Natural Variability of Drought

6.7.1 Variation in Drought Risk with El Niño-Southern Oscillation

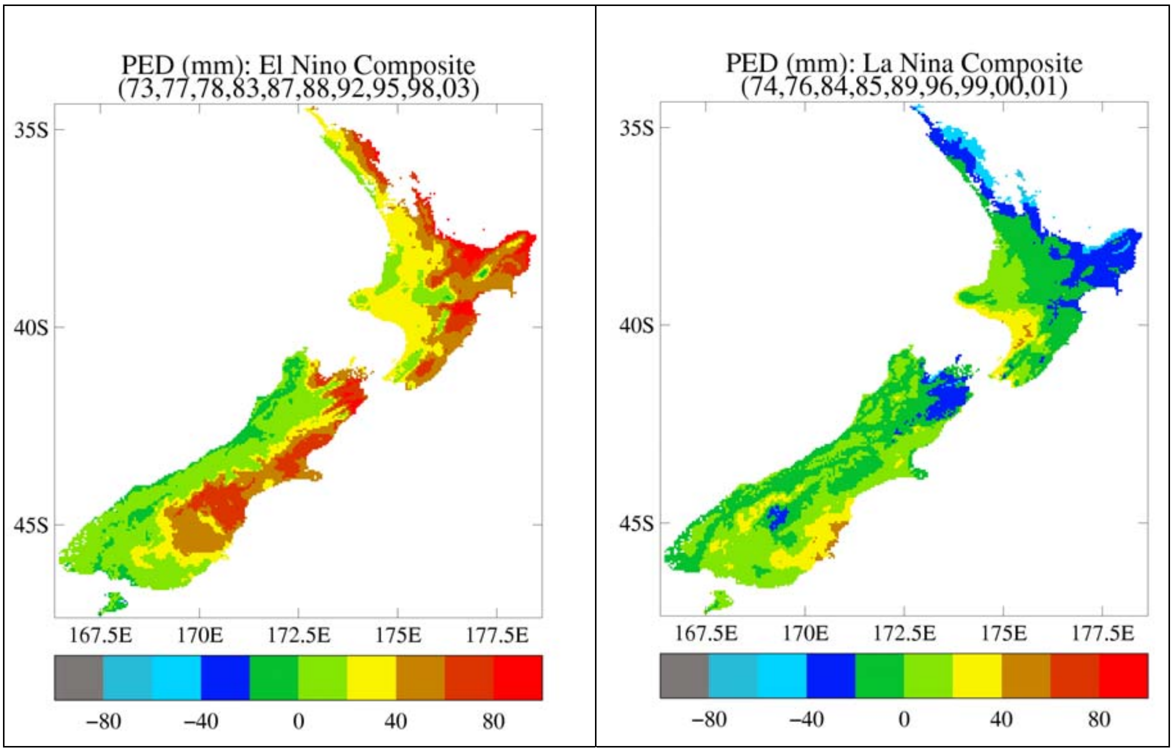


Figure 6.7.1 Average July-June *PED* (mm) composited over El Niño and La Niña periods. The years used in the composite (eg, 1972/73 is first El Niño year) are chosen according to the state of the El Niño-Southern Oscillation over Dec-Feb season.

New Zealand climate varies from year to year, and also decade to decade, and therefore variation in drought incidence can be expected too. One of the main causes of interannual variation in New Zealand climate is the El Niño-Southern Oscillation (ENSO), and the 31-year data set can be used to quantify drought variation with ENSO. The result is shown in Figure 6.7.1, where the July-June *PED* is composited separately over 10 El Niño years (left panel) and 9 La Niña years (right panel). ENSO events do not coincide exactly with our July-June *PED* year, of course. However, the highest evapotranspiration and greatest *PED* deficit accruals occur over summer, and therefore we have characterised the ENSO 'year' according to the tropical Pacific sea surface temperature anomaly (in the so-called Niño-3.4 region) over this season, which is the time of year that ENSO events typically reach their peak (Gordon, 1995).

Figure 6.7.1 shows that there is an average *PED* deficit over most of the country in El Niño years, which is especially marked in eastern areas of both Islands. During La Niña years, the two deficit regions that stand out are Wanganui-Manawatu in the North Island, and coastal Otago in the South Island. Otago is notable for experiencing a deficit under both El Niño circulation (more westerly and therefore drier in the east) *and* La Niña circulation (more anticyclonic and therefore drier over the lower South Island). This nonlinearity of ENSO response, where El Niño and La Niña conditions are not opposite, was first noted by Mullan (1995).

6.7.2 Decadal Variation in Drought Risk

Coherent variations in New Zealand climate over decadal and longer timescales have been identified (Salinger and Mullan, 1999). One of the factors that appears to contribute to this decadal variation is the Interdecadal Pacific Oscillation (Mantua *et al.,* 1997). Three phases of the IPO have been identified during the 20th century: a positive phase (1922–44), a negative phase (1946–77) and another positive phase (1978–98). The pattern associated with the positive phase is higher sea surface temperatures in the tropical Pacific (more El Niño-like) and colder conditions in the North Pacific. Around New Zealand, the sea temperatures tend to be lower, and westerly winds stronger.

The 31-year gridded data set is too short to examine IPO variations, beginning as it does in 1972. However, longer records of *PED* are available from some sites in the NIWA Climate Database. Figure 6.7.2 (Figure 7 in Phase 1 report, Porteous (2004)) shows the mean change in July to June *PED* between the 1950/51-1977/78 period and 1978/79-2002/03 period. Although the figure must be considered preliminary because of the limited number of sites used, the pattern of increasing dryness in the east for the most recent positive IPO phase is consistent with other information on how the Interdecadal Pacific Oscillation affects New Zealand climate (Salinger and Mullan, 1999; Salinger *et al.,* 2001; Wratt *et al.*, 2003).

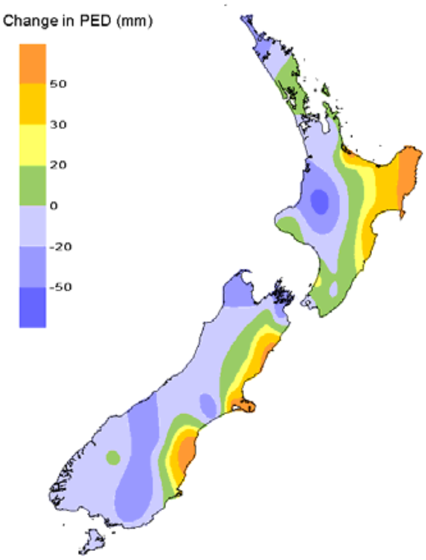


Figure 6.7.2 Mean change in July-June *PED* (in mm) after the 1977/78 season, compared to previous seasons from 1950/51.

6.8 Potential Evapotranspiration Deficit: Current Climate

Figures 6.8.1 and 6.8.2 allow a comparison to be made between the station *PED* calculations of the Phase 1 report and the gridded *PED* calculations of Phase 2. This is an important check on the integrity of the data sets and calculations. Fig. 6.8.1 displays the time series of annual *PED* at Lincoln, using the actual station data, whereas Fig. 6.8.2 gives the corresponding nearest gridpoint data. Most of the annual *PED* accumulation comes during the summer season (true for all other sites as well), with substantial contributions in the spring and autumn seasons for some years. *PED* calculated from the gridded dataset covers a much shorter period, but the interannual variations and absolute magnitude agree well with the station calculations.

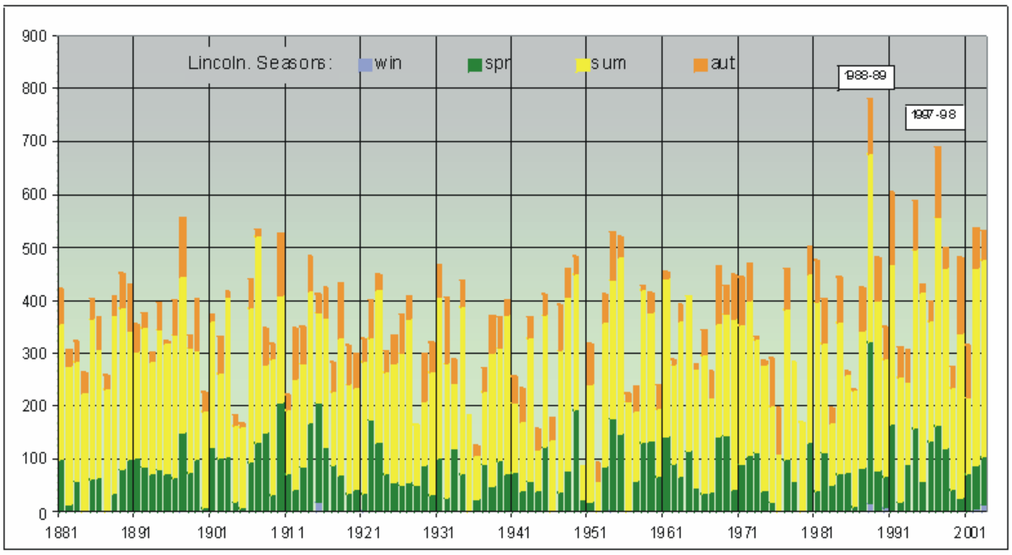


Figure 6.8.1 Accumulated June-May *PED* (mm) at Lincoln, 1881/82 to 2003/04, using data obtained from the NIWA Climate Database. Three-month seasonal accumulations are separated according to colour on each bar. The series highlights 1988/89 and 1997/98 as the most severe droughts in the past 122 years. These two seasons were associated with a strong La Niña and El Niño event respectively. (Figure 1 in Phase 1 report, Porteous, 2004).

At this South Island east coast site, large *PED* accumulations can occur in both El Niño and La Niña years, and occasionally in ENSO-neutral years too such as 1980/81. The longer station time series for Lincoln also suggests there has been an increase in drought severity since the late 1970s, supporting the comments made in the previous section 6.7.2.

Figure 2.1 in the main report shows the accumulated *PED* for the severe drought in 1997/98. Figure 6.8.3 below shows similar maps for two other drought years. The left panel shows that 1982/83, also a very strong El Niño, did not have as great an effect in Canterbury and Otago as the 1997/98 El Niño. The right panel shows the 1988/89 La Niña had a much greater effect in the South Island than the North; this was the worst drought on record at the Lincoln climate site.

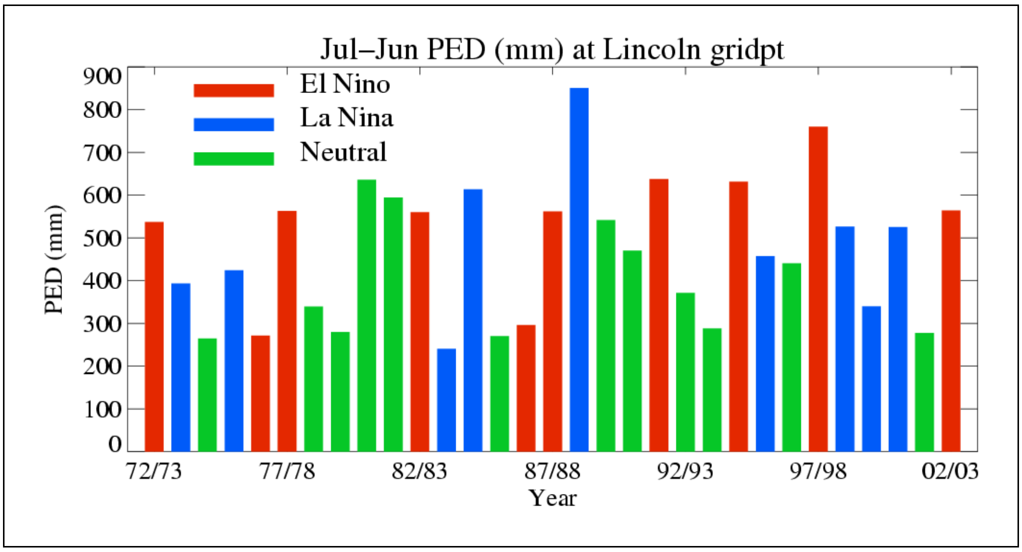


Figure 6.8.2 **Accumulated July-June *PED* (mm) at the gridpoint closest to Lincoln, 1972/73 to 2002/03, extracted from the 0.05° gridded data set. Bars are coloured according to El Niño/La Niña status over the summer season.**

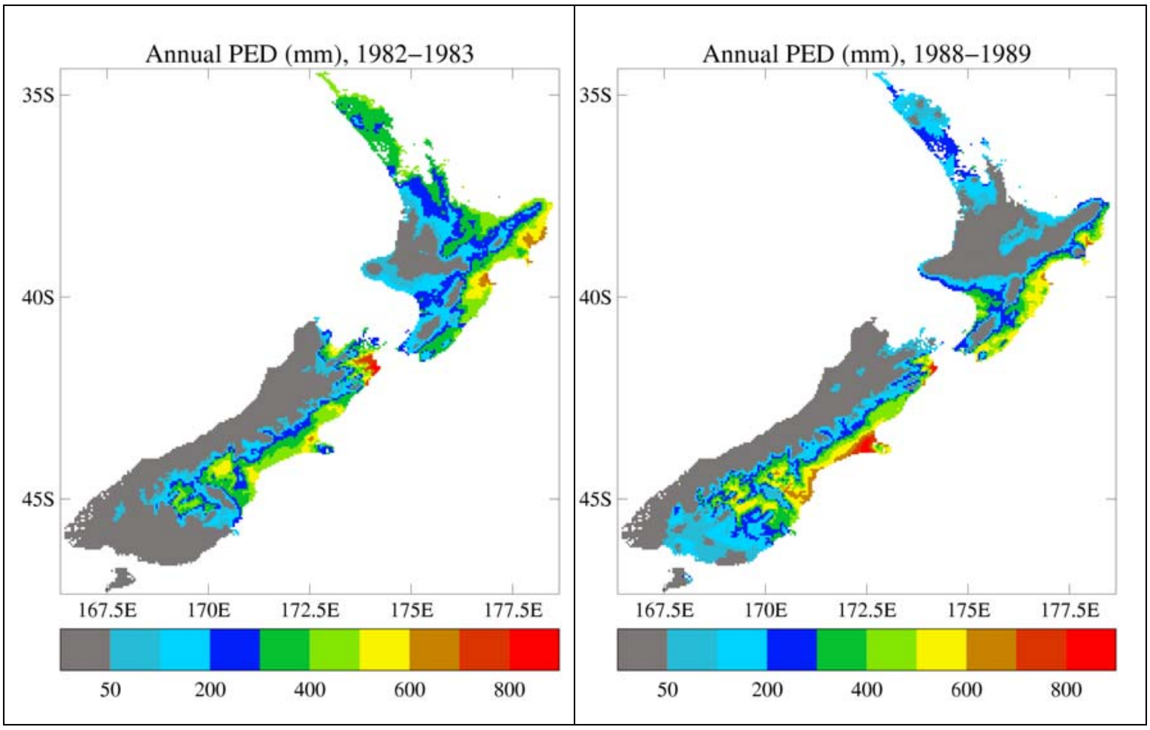


Figure 6.8.3 **Annual *PED* accumulation (mm) for two severe drought years: 1982/83, a strong El Niño; and 1988/89, the worst drought on record at Lincoln.**

In the main report, drought risk is assessed in terms of return period, or probabilities of exceeding a particular level of accumulated *PED*. Numerical methods are available for estimating the probability distribution from a sample of data (31 years of annual *PED*, in our case), and hence calculating the return period for specified exceedance levels. We follow the approach of Kim *et al.* (2003), who describe a non-parametric method for estimating the probability density function (PDF) by using weighted moving averages of the data in a small neighbourhood around the point of estimation, and who apply this method to estimating return periods of drought in Mexico.

Figure 2.3 in the main report shows the probability that in any one year *PED* will exceed 200mm and 600mm. Figure 6.8.4 below shows the corresponding probability for a *PED* exceedance of 400mm, derived from statistical analysis of the historical record.

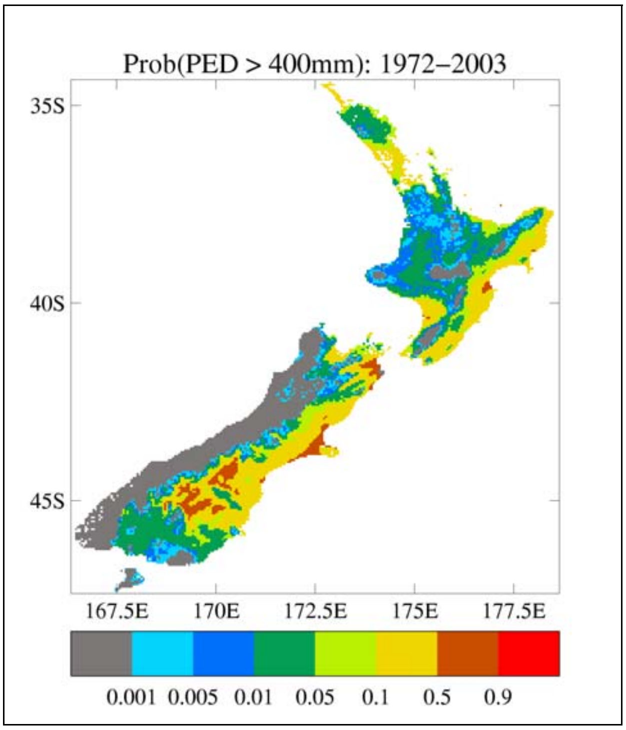


Figure 6.8.4 Probability that in any one year the *PED* will exceed 400mm.

6.9 Potential Evapotranspiration Deficit: Future Scenarios

Because there are four scenarios and two future timeframes (Table 1.1), discussions of future drought in the main report focus mainly on two key sites – Lincoln and Napier. The figures in this section show additional results mapped over the entire country. Figures 6.9.1 and 6.9.2 show the 1-in-20 year return periods for the CSIRO and Hadley scenarios, respectively.

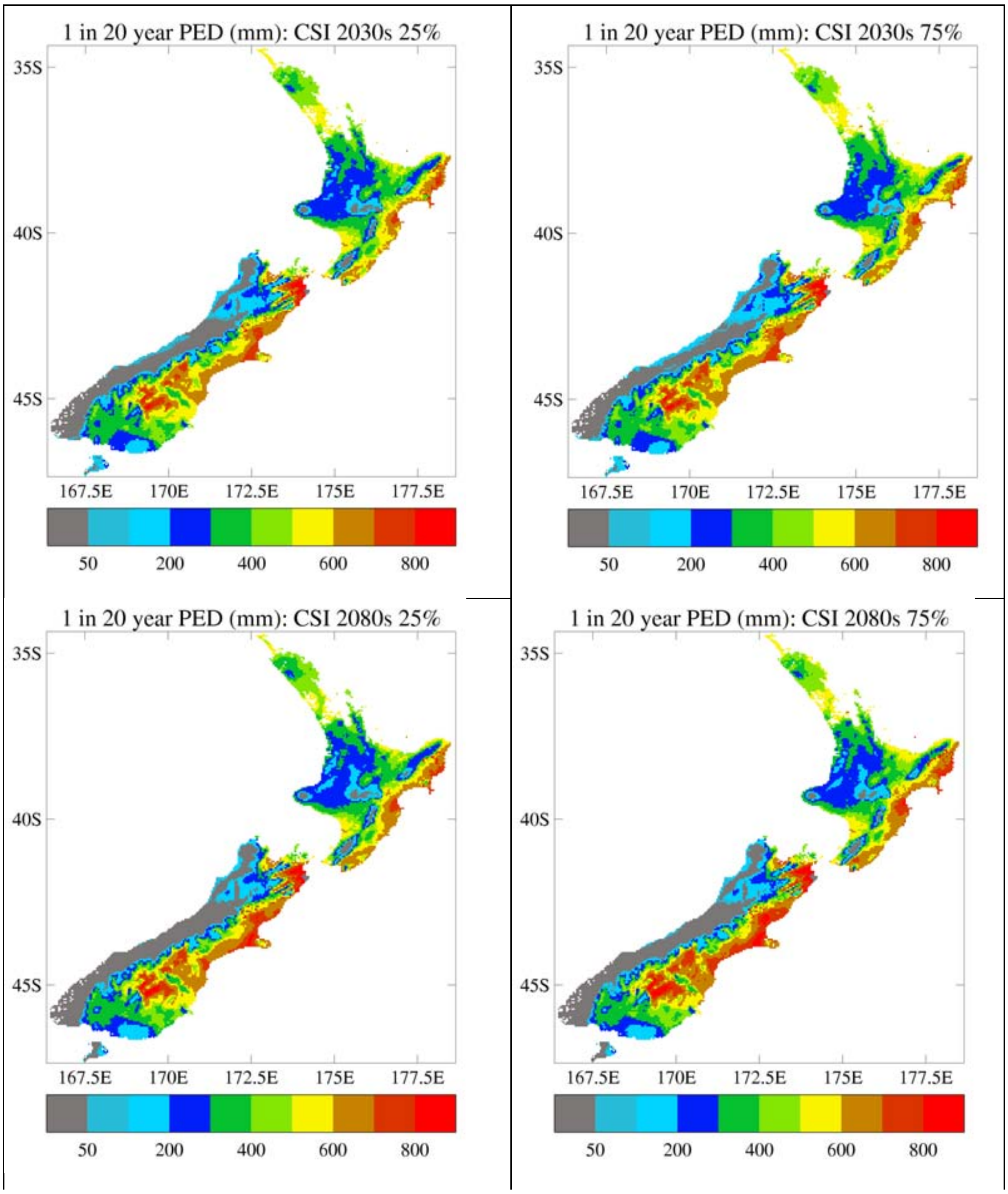


Figure 6.9.1 ***PED*** **(mm) with a 1 in 20 year return period (5% chance of occurrence in any one year) for the four future scenarios based on the CSIRO model.**

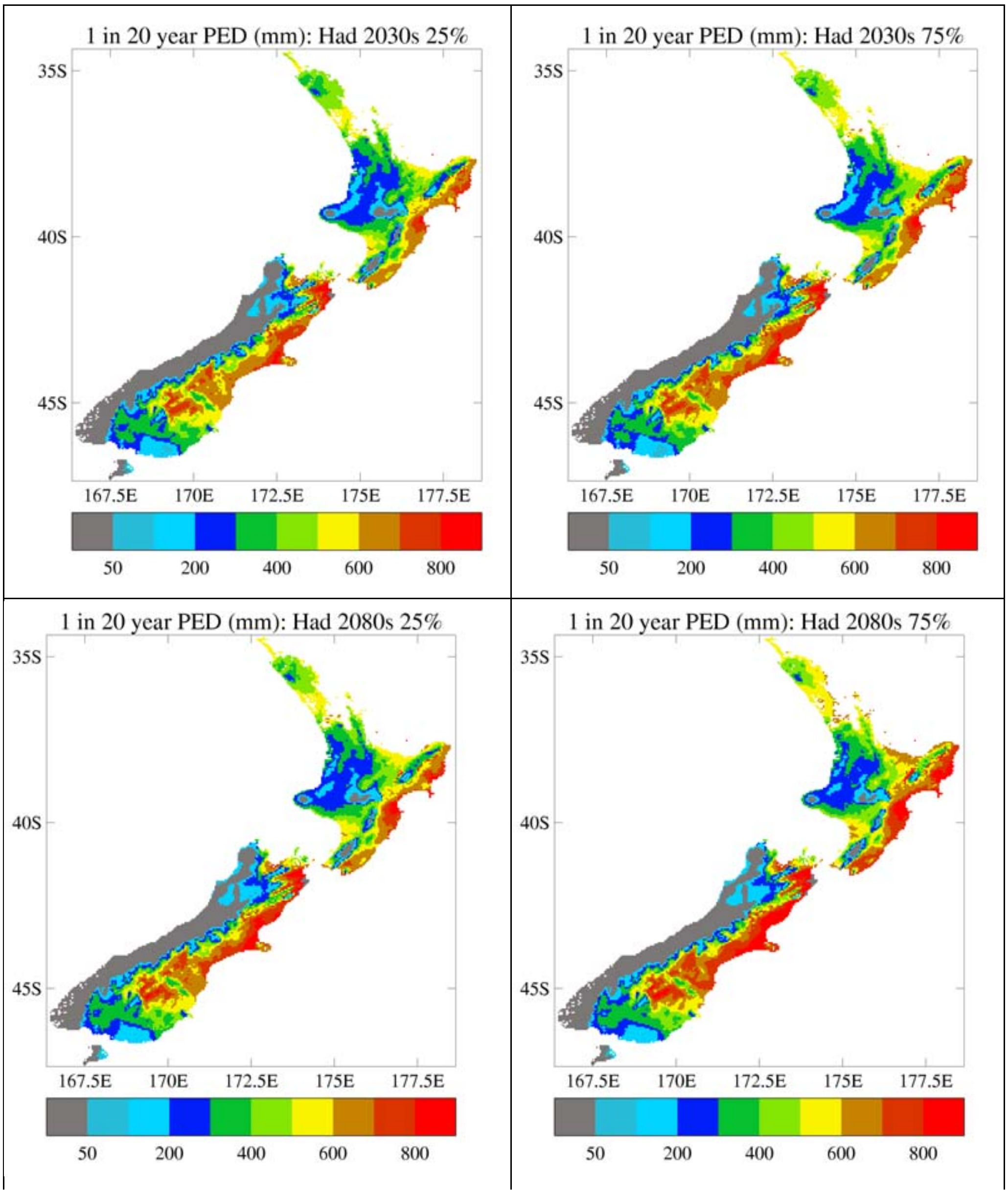


Figure 6.9.2 As Figure 6.9.1, but for the Hadley model.

Drought risk statistics exhibit strong gradients across the country, and thus it can be difficult to see just how the risk varies with the scenario. Differencing of the various maps can clarify these changing risks. Figures 6.9.3 and 6.9.4 show differences in some drought statistics between the present climate and the projected 2080s 75% climates, for the CSIRO and Hadley scenarios respectively.

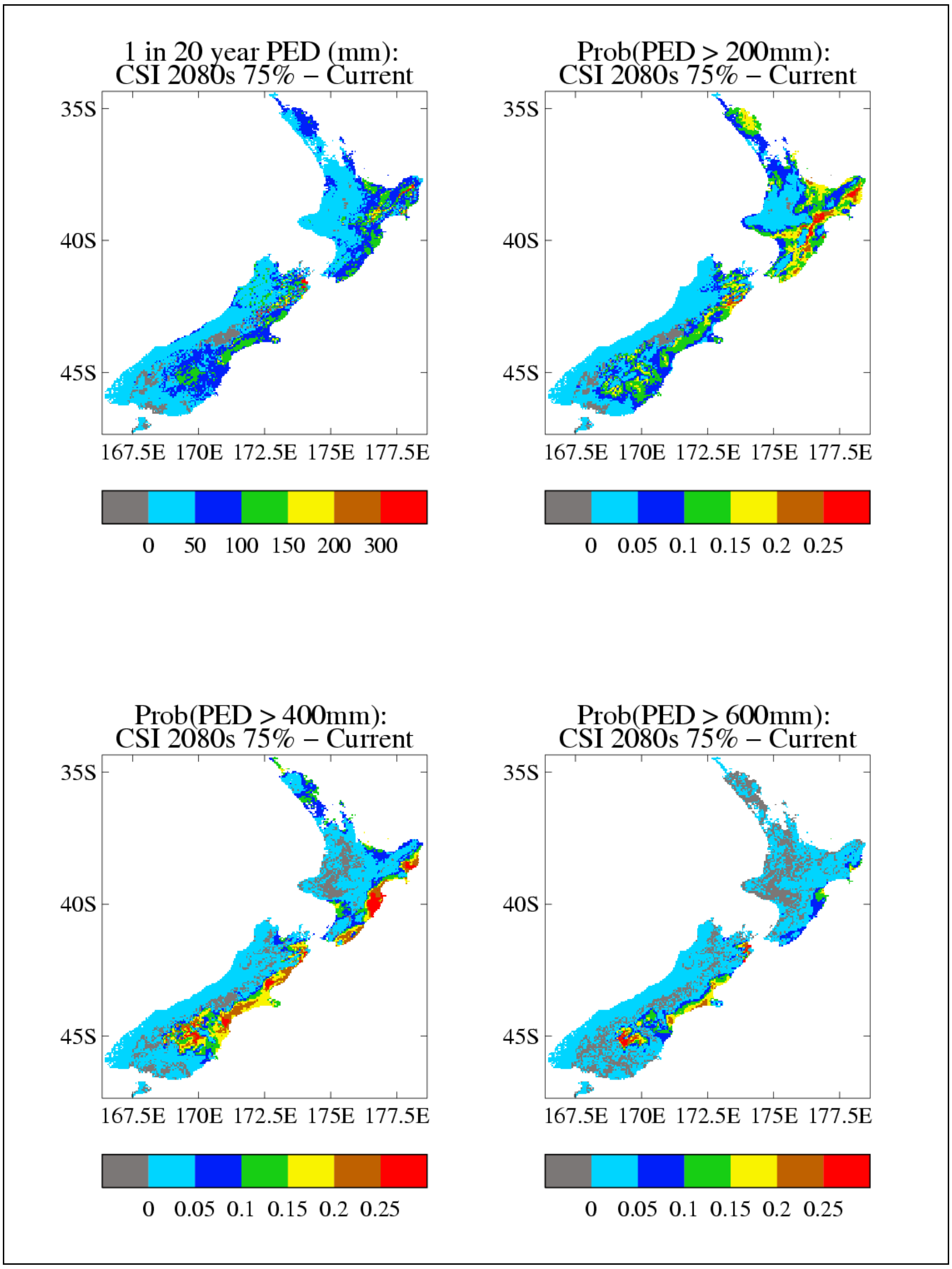


Figure 6.9.3 Change in drought statistics from the present for the CSIRO 2080s 75% scenario.

The top left panel of Figure 6.9.4 shows the value of a 20-year return period *PED* increases by more than 150mm over most of the eastern part of New Zealand, for this most extreme of the eight future scenarios. Changes are relatively larger over the eastern half of the North Island.

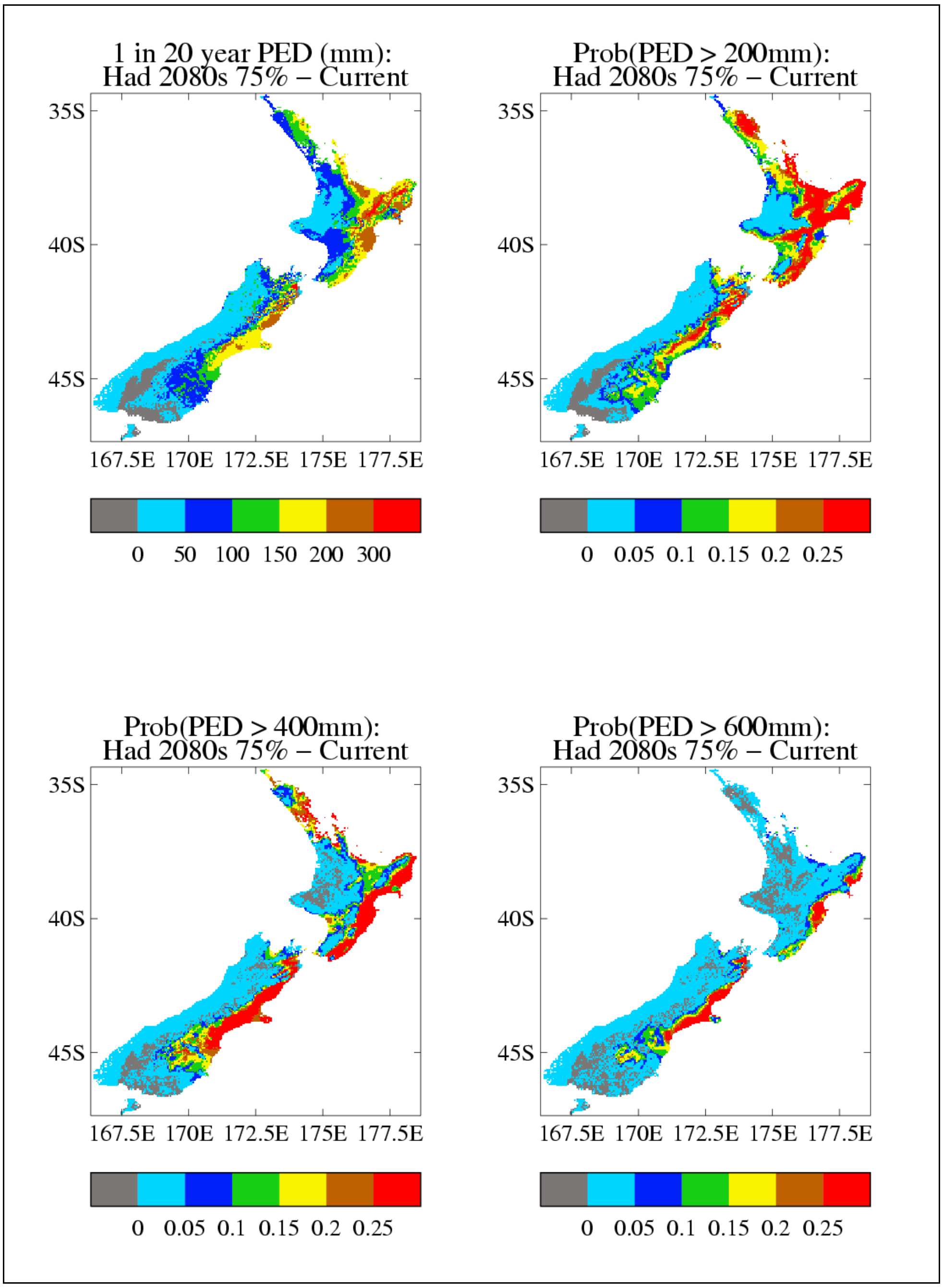


Figure 6.9.4 As Figure 6.9.3, but for the Hadley 2080s 75% scenario.

Figure 6.9.5 shows the future return periods for what are 1-in-20 year *PED* exceedances under the current climate. The return period changes are generally smaller than those in Figure 3.4 (the analogous map for the 2080s), as expected, except for the northern North Island under the CSIRO scenarios. This is a consequence of the CSIRO model not increasing the westerlies smoothly with time. Most of the drying in the northern North Island occurs in the first 50 years, but most of the drying from Napier southwards (e.g., Figure 3.3) occurs in the second 50 years.

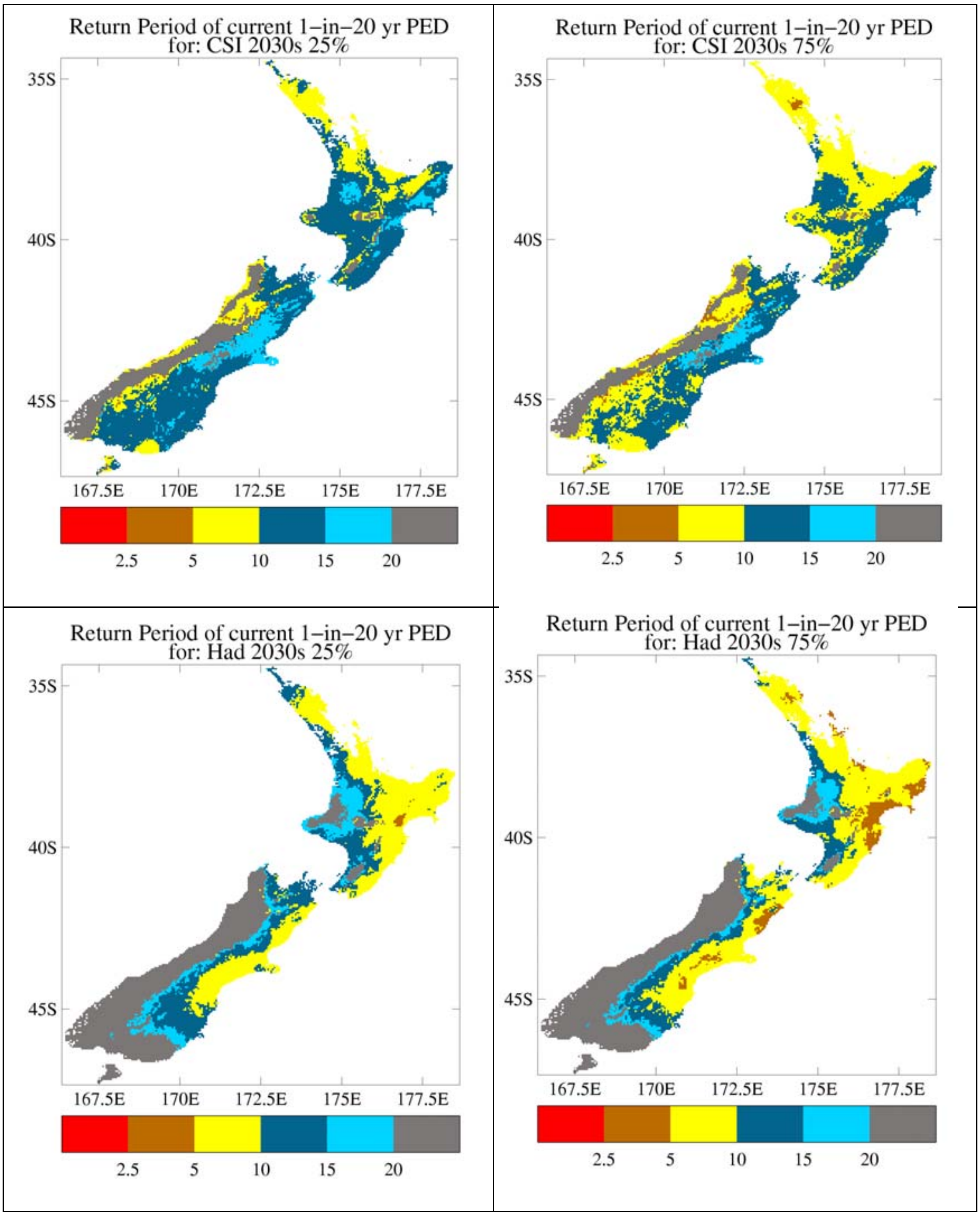


Figure 6.9.5 Future return periods (years) of current climate 1-in-20 year *PED* events, for four scenarios: CSIRO 2030s 25% and 75% scaling (upper panels) and Hadley 2030s 25% and 75% scaling (lower panels). This is the equivalent of Figure 3.4, but for the 2030s instead of the 2080s.

6.10 Change in Probability Distribution of Future Drought

Climate change scenarios project the likelihood that changes in mean climate will be accompanied by changes in the frequency of extreme events. This report has demonstrated that changes in mean rainfall and potential evapotranspiration can indeed lead to an increase in severe droughts in the currently drier regions of New Zealand. There is also the much talked about possibility of increased variability in a warmer climate. In this report, we have assumed no change in daily or interannual variation from the current climate for the driving climate parameters of rainfall and potential evapotranspiration. However, this does not rule out the possibility that the response parameter (*PED*) could become more variable.

Figure 6.10.1 shows the observed distribution of annual (July to June) potential evapotranspiration deficits at three selected sites, Ruakura, Masterton and Blenheim. The data suggest there is more variability at the drier site (Blenheim) with a relatively higher number of extremely dry seasons. That is, the drier Blenheim site has a greater interannual range in the *PED* drought index.

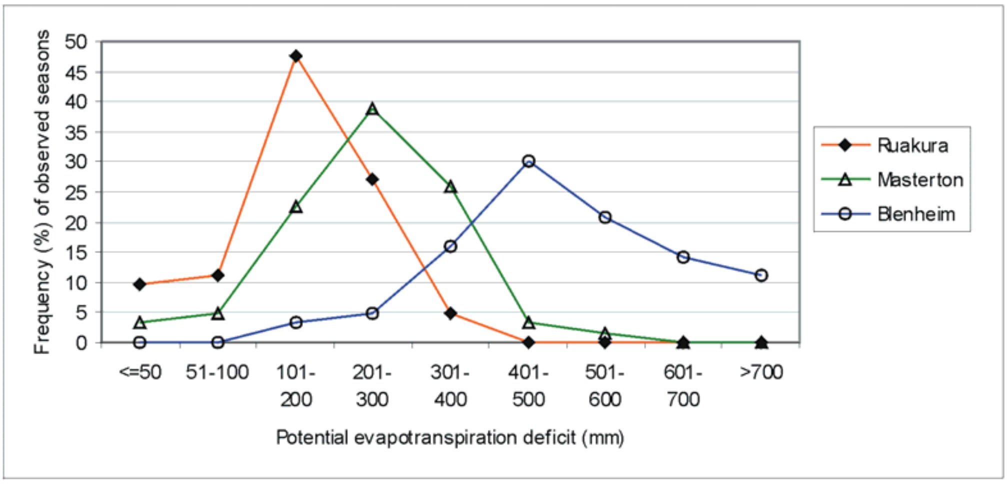


Figure 6.10.1 Frequency (%) of July to June seasons at various levels of potential evapotranspiration deficit, ranging from the wettest site at Ruakura, to progressively drier distributions at Masterton and Blenheim.

Might we expect a similar increase in variability in future drier climates? Figure 6.10.2 illustrates the scenarios changes at the Lincoln and Napier gridpoints, and suggests that indeed this could happen. Figure 6.10.2 focuses on the Hadley 75% scaling as the most extreme; all other scenarios show the same direction of change but are less pronounced. The two panels show the *PED* probability density function for the current climate and for future times, and indicate a substantial shift to the right (higher *PED*) by the 2080s. However, not only is there a change in the mean, but also a change in the variance (a 'broader' distribution). Any increase in variability in the underlying rainfall and *PET* parameters would enhance future *PED* variability further.

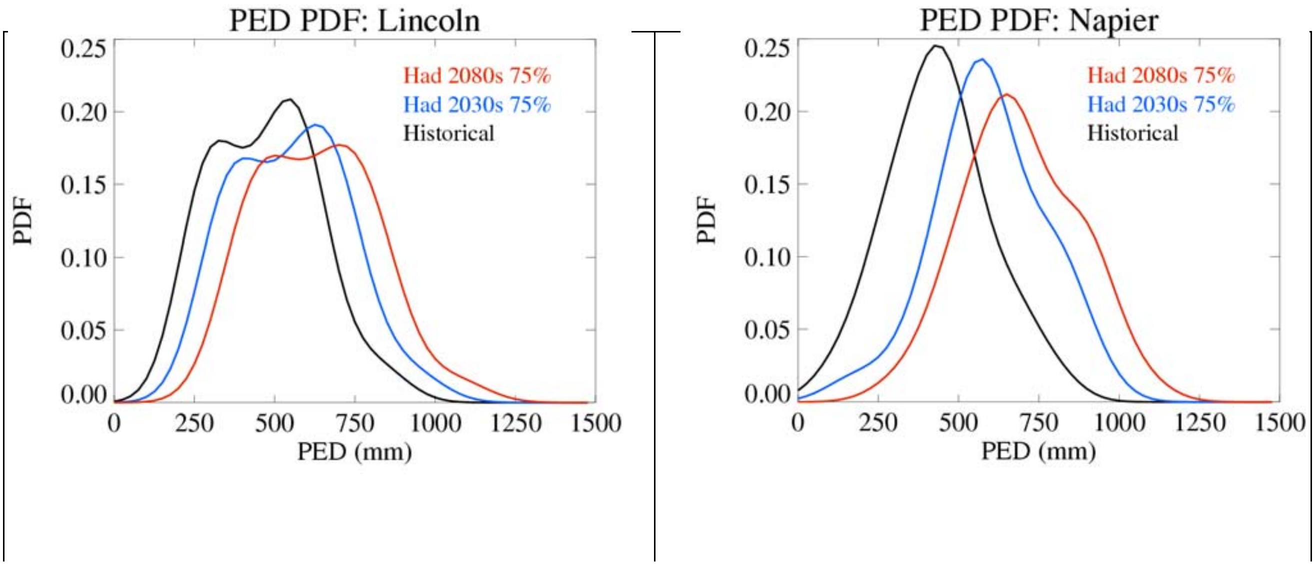


Figure 6.10.2 **Distributional changes in *PED* at the Lincoln (left) and Napier (right) gridpoints, comparing historical distributions with those projected by Hadley model with IPCC 75%ile scaling. The vertical axis for the probability density function (PDF) is normalised such that the area under each curve is unity. Thus the curves with a lower peak frequency compensate by having a larger interannual range.**

6.11 Sensitivity of Results to Stomatal Resistance Changes

There is a well-documented carbon dioxide ‘fertilization effect’, whereby increased atmospheric concentration of CO_2 increases the growth rates of agricultural crops, improves water efficiency and produces higher yields. This has been demonstrated in controlled environments and in field studies using free-air carbon dioxide enrichment (FACE) facilities. However, there is considerable uncertainty about whether these effects can be applied to long-term crop growth over large areas (see Smith *et al.,* 2005, and references therein). For example, a recent review of agricultural ecosystem responses to elevated CO_2 and global climate change concluded “agroecosystem responses will be dominated by those caused directly or indirectly by shifts in climate, associated with altered weather systems, and not by elevated CO_2 per se” (Fuhrer, 2003). Essentially, this is because the associated temperature increase reduces the positive CO_2-only effect, for a number of reasons.

In the New Zealand context, it has been found that soil moisture content under pasture varied little under different imposed CO_2 levels. At the same time, biomass production of New Zealand pasture showed less stimulation to CO_2 enrichment than other grassland ecosystems studied (Morgan *et al*., 2004). Other environmental factors, such as temperature, were not altered in these experiments.

McKenney and Rosenburg (1993) argued that stomatal resistance and plant leaf area are both expected to increase with the higher levels of atmospheric CO_2 associated with climate change. Their work showed that responses in potential evapotranspiration (*PET*) to changes in these two vegetation characteristics are similar in magnitude but opposite in effect – increased stomatal resistance acts to reduce *PET*, whereas greater leaf area acts to increase it. Bunce (2004) noted that, for doubled CO_2, stomatal conductance (inverse of resistance) decreased by anywhere from less than 15% in some crop species to more than 50% in others. However, he concluded that this would translate into less than 10% reduction in evapotranspiration, partly because of increases in temperature and decreases in humidity in the air around crop leaves.

The compensating effects of changes in stomatal resistance and leaf area on *PET* justify our default assumption of no direct CO_2 effect on potential evapotranspiration in this study. However, because there is potentially such a large effect if stomatal resistance effects dominate over leaf area increases, we have carried out a short sensitivity study. We have taken the two extreme 2080s scenarios (CSIRO model with 25% scaling, and Hadley model with 75% scaling) and, after making the scenario *PET* adjustments as before, imposed a 5% reduction in *PET*. Note that this is a reduction on the total *PET*, not just the increment due to increased temperature or stronger winds in a future climate.

Figure 6.11.1 summarises the result in terms of change in current climate 1-in-20 year PED. The left panels are reproduced from the main report Figure 3.4, and show the future return period of events that currently occur on average once in 20 years. Under the default assumption of no CO_2 effect, there are substantial reductions in return period, as discussed in the main report.

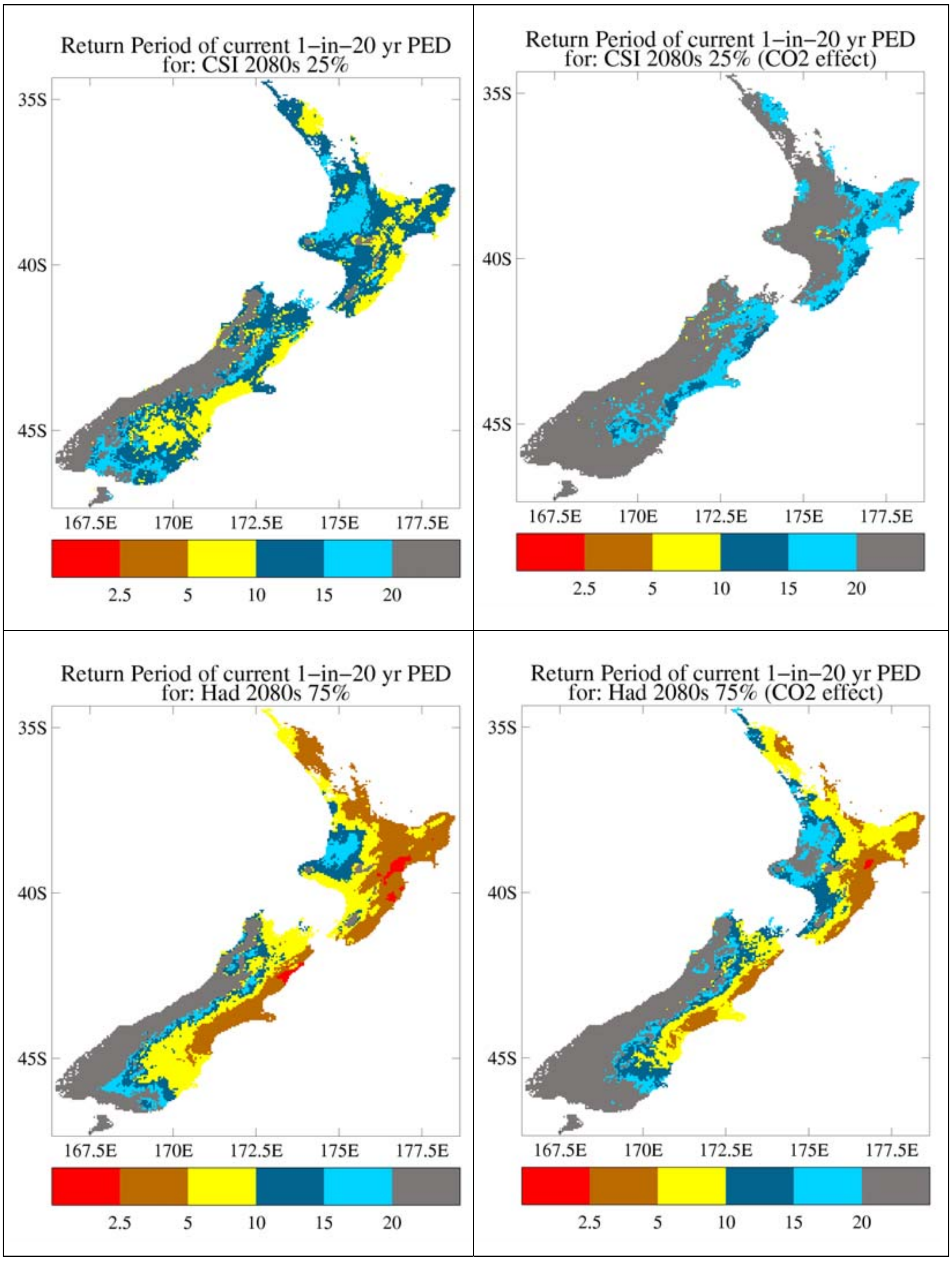


Figure 6.11.1 Future return periods (years) of current climate 1-in-20 year *PED* events, for four scenarios: CSIRO 2080s 25% scaling (top) and Hadley 2080s 75% scaling (bottom), and for standard scenario (left) and with ad hoc 5% *PET* reduction to represent increased stomatal resistance under CO_2 enrichment (right).

The right panels show the future return periods after the 5% reduction in potential evapotranspiration. For the more benign CSIRO 25% scenario, reductions in return period are restricted to eastern margins of both Islands. Even here, the current 1-in-20 year event becomes no more frequent than about 1-in-15 years, in general. However, for the drier Hadley 75% scenario, there are still very substantial reductions in return period throughout eastern parts of New Zealand, from Northland to south Canterbury. Regions where there is a four-fold or more reduction in return period still occur on the eastern margins, although the areas affected contract.

6.12 Overseas studies of changes in drought under global warming

There have been a large number of international studies of changes in water availability under global warming. We have been unable to find a study that is truly comparable to ours in terms of using *PED* as a quantitative indicator of changes in drought risk, and calculating return period changes for drought. Several overseas studies are described briefly below, for the purpose of illustrating that comparable changes in water resources (runoff or some other measure) have been found elsewhere.

Döll *et al*. (1999) calculated global runoff for large drainage basins at 2075, based on one IPCC emissions scenario (IS92a) and two climate model patterns, and assuming climate variability remained constant. The 1-in-10 year dry runoff was computed to decrease by more than 50% in 2.5% and 6.7% of global land area, for the two models. At the same time, there was also an increase of more than 50% in 49.1% and 21.8% of land area, respectively, for the two models, demonstrating that the hydrologic situation became more extreme in many parts of the world.

A recent comprehensive integrated assessment study for the United States (Thomson *et al.,* 2005) considered three model patterns of regional climate change, scaled to match global temperature increases of 1°C and 2.5°C (so there was no specific future date defined), and again assumed no change in interannual variability from the baseline period. The largest changes in water resource were noted in the current semi-arid regions of the western U.S., where changes in water yield, runoff and evapotranspiration exceeding ±50% of baseline levels were identified for the 2.5°C global warming case.

An earlier study by Rind et al. (1990) found even more dramatic changes in the United States from one climate model at about the time of CO_2 doubling. Two drought indices were calculated: the Palmer Drought Severity Index (see appendix, section 6.2.3) and an index measuring excess potential evapotranspiration over precipitation. Both drought indices showed increased likelihood of drought as the climate warmed. In the latter half of the 21st century, when global temperature increases exceeded 4°C, the indices indicated that the "5% drought" (analogous to our 1-in-20 year *PED*) occurred the majority of the time (ie, a tenfold reduction in return period), as an average over the contiguous United States.

Kothavala (1999) used the Palmer Drought Severity Index to quantify changes in drought duration and severity over eastern Australia. A single climate model was used, and 30 years of data around the time of CO_2 doubling were analysed. There was a three-fold increase in the number of months classified as severe or extreme drought in eastern Australia.

There is an intriguing parallel in return period changes between this report on droughts, and other studies on high intensity rainfall. We have found a reduction in return period by a factor of two (for CSIRO 25%) to four or more (for Hadley 75%) by the 2080s. Whetton *et al.* (1996) suggested that by 2070 there would be "no change through to a fourfold reduction in the return period" of daily heavy rainfall events in Australia and New Zealand, based on an equilibrium model study of CO_2 doubling. Hennessy *et al.* (1997), in a similar equilibrium study with two models, confirmed the general finding of a shift in precipitation type to more intense convective events at many locations in middle and low latitudes. For a given intensity of daily precipitation, they found the average return period to shorten by a factor of 2 to 5 across Europe, USA and Australia.

6.13 Appendix References

Adams, P.D.; Horridge, M.; Masden, J.R.; Wittwer, G. (2002). Drought, Regions and the Australian Economy between 2001-02 and 2004-05, *Australian Bulletin of Labour*, *28 (4):* 233-249.

Bunce, J.A. (2004). Carbon dioxide effects on stomatal responses to the environment and water use by crops under field conditions. *Oecologia, 140:* 1-10.

Byun, H.-R.; Wilhite, D. (1999). Objective quantification of drought severity and duration. *Journal of Climate, 12:* 2747-2756.

Cubasch, U.; Meehl, G.A.; Boer, G.J.; Stouffer, R.J.; Dix, M.; Noda, A.; Senior, C.A.; Raper, S.; Yap. K.S. (2001). Projections of future climate change. *In:* JT Houghton, Y Ding, DJ Griggs, et al (eds) *Climate Change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press, 525–82.

Döll, P.; Kaspar, F.; Alcamo, J. (1999). Computation of global water availability and water use at the scale of large drainage Basins. *Mathematische Geologie, 4:* 111-118.

Fuhrer, J. (2003). Agroecosystem responses to combinations of elevated CO_2, ozone, and global climate change. *Agriculture, Ecosystems and Environment, 97:* 1-20.

Gardiner, P. (2001). An assessment of the Asian crisis and droughts: 1991-2000. A New Zealand Institute of Economic Research report to the Ministry of Agriculture and Forestry, May 2001.

Gordon, N.D. (1986). The Southern Oscillation and New Zealand weather. *Monthly Weather Review, 114:* 371–387.

Hennessy, K.J.; Gregory, J.M.; Mitchell, J.F.B. (1997). Changes in daily precipitation under enhanced greenhouse conditions. *Climate Dynamics, 13:* 667-680.

Kim, T.-W.; Valdes, J.B.; Yoo, C. (2003). Nonparametric approach for estimating return periods of droughts in arid regions. *ASCE Journal of Hydrologic Engineering, 8(5):* 237-246.

Kothavala, Z. (1999). The duration and severity of drought over eastern Australia simulated by a coupled ocean-atmosphere GCM with a transient increase in CO_2. *Environmental Modelling and Software, 14:* 243-252.

Laughlin, G.; Clark, A. (2000). Drought science and drought policy in Australia: a risk management perspective. *Expert Group meeting on Early Warning Systems for Drought Preparedness and Drought Management,* Lisbon, September 2000. Bureau of Rural Sciences, Dept of Agriculture, Fisheries and Forestry-Australia, Kingston, ACT.

McKenney, M.S.; Rosenberg, N.J. (1993). Sensitivity of some potential evapotranspiration estimation methods to climate change. *Agricultural and Forest Meteorology, 64:* 81-110.

Mantua, N.J.; Hare, S.R.; Zhang, Y. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society, 78:* 1069-1079.

Morgan, J.A.; Pataki, D.E.; Körner, C.; Clark, H.; et al. (2004). Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO_2. *Oecologia, 140:* 11-25.

Mullan, A,B. (1995). On the linearity and stability of Southern Oscillation-climate relationships for New Zealand. *International J. Climatology, 15:* 1365-1386.

Palmer, W.C. (1965) Meteorological Drought. *US Weather Bureau Technical Paper 45,* 1-58.

Rind, D.; Goldberg,R.; Hansen, J.; Rosenzweig, C.; Ruedy, R. (1990). Potential evapotranspiration and the likelihood of future drought. *Journal of Geophysical Research, 95:* 9983-10004.

Salinger, M.J.; Mullan, A.B. (1999). New Zealand climate: temperature and precipitation variations and their links with atmospheric circulation 1930–94. *International Journal of Climatology, 19:* 1049-1071.

Salinger, M.J.; Renwick, J.A.; Mullan, A.B. (2001). Interdecadal Pacific Oscillation and South Pacific climate. *International Journal of Climatology, 21:* 1705-1721.

Shafer, B.A.; Desman, L.E. (1982). Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snow pack runoff areas. *Proc. Western Snow Conference,* 164-175.

Smith, S.J.; Thomson, A.M.; Rosenberg, N.J.; Izaurralde, R.C.; Brown, R.A.; Wigley, T.M.L. (2005). Climate change impacts for the conterminous USA: An integrated assessment. Part I: Scenarios and context. *Climatic Change, 69*: 7-25.

Thomson, A.M.; Brown, R.A.; Rosenberg, N.J.; Srinivasan, R.; Izaurralde, R.C. (2005). Climate change impacts for the conterminous USA: An integrated assessment. Part 4: Water resources. *Climatic Change, 69:* 67-88.

Trenberth, K.R. (1976). Fluctuations and trends in indices of the Southern Hemisphere circulation. *Quarterly Journal of the Royal Meteorological Society, 102:* 65-107.

USDA (2000). Preparing for Drought in the 21st Century - *Report of the National Drought Policy Commission,* May 2000. United States Department of Agriculture.

Western Drought Coordination Council. (1998). How to reduce drought risk. *Report of the Preparedness and Mitigation Working Group.* National Drought Mitigation Centre, University of Nebraska-Lincoln, http://enso.unl.edu/wdcc/.

Whetton P.; Mullan, A.B.; Pittock, A.B. (1996). Climate change scenarios for Australia and New Zealand. In: *Greenhouse 94, Coping with Climate Change*, Eds: W.J. Bouma, G.I. Pearman and M. Manning. CSIRO/DAR, Melbourne, pp. 145-168.